

ANALYSIS OF THE
DECAMETER-WAVELENGTH RADIO
EMISSION FROM THE PLANET JUPITER

By
NORMAN FRANK SIX, JR.

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CHAPTER I

INTRODUCTION

The discovery that Jupiter is a strong, intermittent source of non-thermal radio-frequency energy was made in 1955 by Burke and Franklin (1). The following year the University of Florida Radio Observatory began systematic observations of Jupiter at a frequency of 18 Mc/s. Since that time, the program has been expanded to include radio-frequency monitoring in the range between 5 and 31 Mc/s. Jupiter has not been the only subject under investigation. Observations have been made of Saturn, Uranus, Venus, and Mars, and in 1959 a southern hemisphere field station was established at Maipú, Chile.

Planetary Observing Program with Emphasis on Jupiter

The Decameter-Wavelength Range

The radio astronomy group at the University of Florida has concerned itself principally with planetary radiation in the "tens-of-meters" wavelength range. Observations of Jupiter, Saturn, Uranus, Mars, and Venus have been made. The results are negative for Uranus, Venus, and Mars. (From records taken in 1960, we concluded that Venus did not emit non-thermal decameter-wavelength radiation of flux density greater than 5×10^{-22} watts/m²/cps (2).)

The results for Saturn are inconclusive. In 1960 there were seven weak events possibly of Saturnian origin. Matters were complicated by the fact that Jupiter and Saturn were separated throughout the apparition by approximately one hour in right ascension. Again during the 1961 apparition there were several occasions of possible Saturn radiation, none of which was conclusive. With the greater separation of Jupiter and Saturn relaxing the resolution requirement, it is hoped that the 1962 observing season will establish the existence or nonexistence of decameter-wavelength radiation from the ringed planet.

Jupiter appears to be unique among the planets. As far as we know, none of the other bodies which circle our sun (with the possible exception of Saturn) are strong emitters of non-thermal radio noise. Considering extraterrestrial sources, the powerful Jovian outbursts in the decameter-wavelength range are exceeded in intensity only by the sun. Thus, it is not surprising that this new avenue to information about the giant planet has been the main concern of the University of Florida group.

Kinds of Radiation

The radio emission from Jupiter is caused by at least three distinct mechanisms. Table 1 divides the radiation into three components according to wavelength and presents empirical evidence relating to the origin of each.

The apparent black body disk temperature is the temperature that a hypothetical black body, which subtends the same solid angle

TABLE 1
Types of Radio Emission from Jupiter

Wavelength region	Investigators	Apparent black body disk temperature	Energy distribution	Mechanism
Centimeters	Mayer, McCullough, Sloanaker 3.15 cm. (3)	$145^{\circ} \pm 18^{\circ} \text{ K}$	$E \propto \lambda^{-2}$	Thermal emission
Tens of centimeters (decimeter)	Sloanaker 10.3 cm.	$640^{\circ} \pm 57^{\circ} \text{ K}$	$E \approx \text{constant}$	Clearly non-thermal (synchrotron emission)
	McClain 21 cm.	$2500^{\circ} \pm 450^{\circ} \text{ K}$		
	Roberts and Stanley 31 cm.	5500° K		
Tens of meters (decameter)	Drake and Hvatum 68 cm. (4)	50000° K	$E \propto \lambda^{3.6}$	Clearly non-thermal (?)
	University of Florida 9.7 m. (31 Mc/s) to 60 m. (5 Mc/s) (5)	$2.5 \times 10^{10} \text{ }^{\circ}\text{K}$ at $\lambda = 16.7 \text{ m.}$ (18 Mc/s)		

as the visible disk of the planet, would have if it emitted thermal radiation of the same intensity as the observed radiation. The values for the apparent black body disk temperatures in the first two wavelength regions in the table were obtained from reference (4). This reference also contains a graph showing the variation in apparent disk temperature with wavelength. The Rayleigh-Jeans approximation to the Planck black body curve well describes the energy distribution of the thermal radiation at radio wavelengths. The temperature 145° K agrees well with infrared measurements (6). The spectral distribution of the two non-thermal components of radiation will be discussed later as will the mechanisms involved.

Types of Studies

Since 1956, five major problem areas have shown up in the analysis of the decameter records and consequently these have received the most attention. They are as follows:

1. localized sources
2. polarization
3. spectrum analysis
4. influence of the terrestrial ionosphere
5. solar correlations

The decameter radiation comes from "hot spots" which are localized or fixed in longitude System III (2). These sources rotate with a period of $9^{\text{h}} 55^{\text{m}} 29.35^{\text{s}}$. If we plot the probability of receiving Jovian radiation when a 5° increment of longitude is on the central meridian of the illuminated disk versus System III longitude, the

localization of the sources is quite evident. There appear to be three main sources and some of these show a tendency to split. The radiation at different frequencies comes from slightly different longitudes and at very low frequencies the source structure is lost altogether.

Polarization studies of the radiation have revealed that the polarization does not occur in the terrestrial ionosphere, but is characteristic of the Jovian signals. These studies provide evidence for the existence of a magnetic field on Jupiter and lay a foundation for testing parameters such as the magnetic field strength and the ion density in Jupiter's ionosphere, both of which are of fundamental concern in trying to discover a "model" which explains the origin of the decameter radiation.

Spectrum analysis yields information about the structure of the individual pulses and bursts of radiation, and how they drift up or down the frequency spectrum. Here again, knowledge of how the energy is distributed with frequency is a must for determining what mechanism is involved.

The influence of the terrestrial ionosphere must be classified as one of the unsolved questions. From high speed recordings taken at the stations in Florida and Chile at the same frequencies, it is obvious that the ionosphere is altering the pulse structure. It is only on rare occasions that we get pulse to pulse correlation in time. We believe that inhomogeneities and clouds of ions in the ionosphere are responsible. The differences in the axial ratios of the polarization ellipses at the two stations are too great to be accounted for by the measured ion densities in our ionosphere (7).

Solar correlations have been attempted to find if there is any connection between the Jovian decameter radiation and the bursts of particles and radiation from the sun. In some cases, correlations have been found. The solar related variables under inspection have been the following: sunspot number, solar flares, geomagnetic storms, solar m-regions, and terrestrial polar cap absorptions.

Instrumentation

The microwave observations are carried out with large parabolic antennas and low-noise amplifiers, since receiver noise is the principal limitation. The decameter work is conducted with conventional antenna arrays and standard communications receivers, the principal limitation being "atmospherics" and man-made noise. The background signal from the galaxy at the longer wavelengths is greater than the receiver noise, so there is not much to be gained by going to low noise devices.

The major equipment at the Florida observatory includes two 18 Mc/s Yagi antennas on equatorial tracking mounts to provide discrimination between Jupiter and Saturn; a 27 Mc/s Yagi on an equatorial tracking mount; an 8-element 18 Mc/s broadside array (a description of a similar antenna is found in reference (8)); two 32-element 22.2 Mc/s broadside arrays, which can be used as a lobe-switching interferometer (9, 10, 11); a broad-band rhombic array for use with a swept-frequency receiver, which displays any 4 Mc/s segment of the spectrum up to 25 Mc/s on a cathode-ray tube (12); and a 22.2 Mc/s polarimeter consisting of crossed Yagis on a steerable boom (13, 14). There is

also a 90° corner reflector, steerable in altitude and operable in the frequency range from 14 to 31 Mc/s through the use of appropriate dipoles (15).

The major instrumentation in Chile includes two steerable 18 Mc/s 8-element broadside arrays, which track a planet automatically by means of a motorized phasing device; 5, 10, 15, and 20 Mc/s broadside arrays; a 22.2 Mc/s polarimeter consisting of four folded dipoles over a tilted ground plane; a 16 Mc/s crossed Yagi polarimeter on an alt-azimuth mount; and a mechanically steerable corner reflector identical with the one in Florida.

Signals from all the antennas are amplified by commercial communications receivers and recorded on pen recorders. A standard recording speed of 6 inches/hour is used, with high speed recorders at each station making auxiliary recordings at 5 mm./sec. during intervals of planetary activity. Motion-picture recording of the scope display of the swept-frequency receiver is employed during Jupiter outbursts. The receiver-recorder systems are calibrated for absolute flux levels by means of noise diodes. Time marks are placed on all records by timing systems calibrated against the signals from WWV. Short-wave transmitting equipment is used at both observatories for the interchange of data and instructions. An observer is on duty at each observatory during all periods of recording to monitor the signals, eliminate interference, and perform special experiments.

In addition to the observing programs conducted in Florida and Chile, Dr. T. D. Carr of the Gainesville group spent the period of

June 17 - August 30, 1961, in Australia monitoring Jupiter radiation at the Fleurs field station of the Radiophysics Division, Commonwealth Scientific and Industrial Research Organization. Instrumentation included a 10 Mc/s fixed beam array of 2 full-wave dipoles and a 19.7 Mc/s linear array of 43 half-wave dipoles, a portion of the north-south arm of the Mills Cross built by Shain (16). Two such arrays phased for different directions were used to permit longer observing.

CHAPTER II

JUPITER DATA IN 1961 AND COMPARISON WITH PREVIOUS YEARS

Analysis

Raw Data

Pen recordings of the radiation monitored in Florida and Chile are taken on Texas dual channel recorders at a chart speed of 6 inches/hour. These records are analyzed, and the following information is taken from them: date, frequency monitored, observing station, beginning and end of the listening period in Universal Time (hours and minutes, e.g., 0745), beginning and end of the Jovian activity period, intensity of the activity, and pertinent remarks concerning such things as listening conditions, degree of certainty in identifying the radiation as Jovian, structure of the signals, and equipment troubles.

The procedures involved in obtaining some of the above information need to be explained. Since quite frequently the observing periods span midnight, Eastern Standard Time, more than one date would be involved. This would make it difficult to correlate daily indices such as sunspot number with the activity during a watch period. To avoid the difficulty and others, the following convention regarding the date of a watch period has been adopted. The 24-hour period beginning at 12 noon Eastern Standard Time, date x, and ending at 12 noon Eastern Standard Time, date y (where $y = x + 1$), is designated the period of

date y . An observing period occurring any time in this interval is called the watch of date y . It is extremely unlikely that the Jupiter watches at either the Chile or Florida station will ever straddle 12 noon Eastern Standard Time.

The listening period is that part of the watch during which receiving conditions are good enough to permit detection of Jupiter radiation. Limits on the listening periods are also imposed by the antenna patterns of the non-steerable arrays. During 1961 the effective listening periods of the systems using the following arrays were limited to ± 4 hours from Jupiter transit of the station meridian: 5 Mc/s broadside, 22.2 Mc/s polarimeter, and the 27.6 Mc/s corner reflector in Chile; the 15 and 31 Mc/s corner reflector in Florida. The beam limits of the 22.2 Mc/s polarimeter at the Florida station were ± 3 hours from the direction of pointing. From February 25, 1961, through September 19, 1961, it was pointed due south. During September 20 - 30, 1961, it was pointed 40° west of south.

The listening periods of the systems utilizing steerable arrays were restricted to altitudes of the planet greater than 5° . Conversion of right ascension and declination to altitude and azimuth was facilitated by use of a nomogram. The antenna pattern limits and the altitude limits were determined experimentally by checking to see how often radiation was received outside of these regions.

The Australian data collected during June 17 - August 30, 1961, were handled specially. The convention explained above regarding the date of an observing period would not work; so, for this data a 24-hour

period beginning at 0^h U.T. was used. Listening period limits due to antenna patterns were not applied.

The relative intensity of a Jupiter radio storm is arrived at by taking the average deflection above the galactic level of the three highest peaks during the activity period and dividing by the galactic level (17). If there is a break in the activity of more than 8.3 minutes, corresponding to a 5^o rotation of Jupiter, then we consider the separate parts as two Jovian storms. The comments concerning listening conditions and description of the radiation provide a basis for deciding upon the authenticity of the Jovian signals.

Jupiter Program for the IBM 709

A yearly analysis program for the IBM 650 computer was developed in 1960 (18). Since that time the University of Florida has replaced the 650 with an IBM 709 computer. The original yearly analysis program has been rewritten with many additions, deletions, and corrections.

The input to the 709 is put on punched cards and consists of the previously mentioned raw data:

- a. station
- b. date (month, day, year)
- c. frequency
- d,e. listening period beginning and end in U.T.
- f,g. activity period beginning and end in U.T.
- h. intensity of the Jovian radiation

plus the following information:

- i. normalization constant: This compensates for the change in galactic level between the 1957 position of Jupiter and subsequent positions.
- j. daily sunspot number: Obtained from N.B.S. Solar-Geophysical Data Part B.
- k. λ_{II}^h U.T.: This is the longitude in System II (19) of the central meridian of the illuminated disk of Jupiter at 0^h U.T. on the date in question. See the American Ephemeris and Nautical Almanac.
- l. Julian day number: Found in the American Ephemeris and Nautical Almanac.

The last three of the above items are daily parameters and must be selected according to date of the watch period as determined by the previously mentioned procedure. In putting the data on punched cards, the listening periods must be split in many cases so that there is only one activity period in each listening period. Thus, there will be a card for each activity period.

Seven major computations are performed by the 709 in the Jupiter program. We shall consider each separately.

Computation of the beginning and end of the listening and activity periods in System III longitude. The rotation period of the radio sources is $9^h 55^m 29^s.35$ (2). The designation "System III" has been given to the longitude system which rotates with this period and was coincident with System II at 0^h U.T. on January 1, 1957. The System III longitude of the central meridian at 0^h U.T. on Julian date J is found

by means of the equation

$$\lambda_{III}^{0^h} = \lambda_{II}^{0^h} + 0.2747 (J - 2435839.5). \quad [1]$$

$\lambda_{II}^{0^h}$ is input item k; J is input item l; the constant 0.2747 is the drift in degrees/day between systems II and III; and 2435839.5 is the Julian day number of January 1, 1957, the date when the two systems coincided. The System III longitude at H hours M minutes before or after 0^h U.T. is obtained from the relationship

$$\lambda_{III} = \lambda_{III}^{0^h} \mp 36.27 (H) \mp 0.6045 (M). \quad [2]$$

The minus signs are used if we want the λ_{III} corresponding to a Universal Time H hours and M minutes before 0^h U.T. The plus signs are used for a U.T. after 0^h U.T. The computer checks each U.T. and makes the correct choice of signs. This method of performing the computation is necessary because of the convention adopted regarding the date of an observing period. The constants 36.27 and 0.6045 are degrees of rotation per hour and degrees of rotation per minute, respectively, for System III.

Computation of the activity index for each activity period. The activity index is calculated as follows (20):

$$\text{activity index} = (\text{intensity}) \cdot (\text{duration of the activity period in minutes}) \cdot (\text{normalization constant}). \quad [3]$$

Remember that the intensity of a storm is the average height above the galactic level of the three highest peaks, taken as a ratio to the galactic noise level. This is input h; the normalization constant is input i; and the duration of the activity period is obtained from

inputs f and g. The activity index, as its name implies, is a measure of how active Jupiter is and contains the factors intensity and duration.

Computation of the daily activity index rate. The computer uses the equation

$$\text{daily activity index rate} = \frac{\sum_a (\text{activity index})_a}{\sum_a (\text{duration of listening period in minutes})_a} \quad [4]$$

to compute the daily activity index rate. "a" runs over all the listening periods on a day. Remember that in input form the listening periods were split so that there was never more than one activity period in each listening period. Notice the division by the duration of the listening period. This is done to obtain a measure of the rate of activity.

Computation of the monthly activity index rate. This is found using the above equation, where a runs over all the listening periods in a month.

Computation of the apparition activity index rate. Again the same equation is used and a runs over all the listening periods in the apparition.

Computation of the monthly average sunspot number. Using the equation

$$\text{monthly average sunspot number} = \frac{\sum \text{daily sunspot numbers}}{\text{number of days in the month}}, \quad [5]$$

the computer determines the average sunspot number for each month.

Generating the probability histogram table. For each 5° increment of System III longitude, the computer counts the number of times that Jovian radiation was received and the number of times the station was listening effectively, while any part of that 5° increment of longitude was on the central meridian of the illuminated disk. The probability of getting radiation from Jupiter when a particular 5° increment is on the central meridian is the quotient obtained by dividing the former by the latter. Seventy-two such values, one for each 5° of longitude, comprise the histogram table. The count can be taken over an entire apparition, several apparitions, or just part of an apparition, depending on what cards are fed to the 709.

If listening or activity occurs in any small part of a 5° increment of longitude, the program considers that the complete 5° was listened to or had activity in it. This results in a slight smearing of the data. When a listening period is split so that there will be no more than one activity period in each listening period, then the 5° increment of System III longitude in which the split is made is counted as being listened to twice. Because of the random positions of the splits, it is felt that this state of affairs does not appreciably alter the histogram tables.

The printout sheets from the 709 Jupiter program contain all of the input data except the Julian day number, and in addition the following:

- listening period beginning and end in System III longitude
- activity period beginning and end in System III longitude
- activity index for each activity period

daily activity index rate
 monthly activity index rate
 apparition activity index rate
 monthly average sunspot number
 probability histogram table

Merge Program for the IBM 709

The purpose of the merge program is to combine the data taken at the observatories in Florida and Chile in order to get the best station-wide activity period and listening period. By merging the data taken on a particular day at the two stations, we obtain a more realistic picture of how Jupiter was behaving. With two-station coverage, conditions at a single station, such as equipment failures, interference, or bad atmospherics do not result in no data for that period. As an example of how the merge program works, suppose that on June 10 the effective listening at the Florida station was from 0600 to 1030 U.T. and in Chile from 0415 to 0545 and from 0900 to 1200 U.T. After merging, the effective listening period would be 0415 to 0545 and 0600 to 1200 U.T.

The input to the merge program consists of the same cards used in the Jupiter program except that the Chile and Florida cards must be collated before putting into the 709 so that the dates are in order. The output of the merge program consists of the date, frequency, merged listening period beginning and end in U.T., merged activity period beginning and end in U.T., λ_{II} for 0^h U.T., and the Julian day number. These data are punched into cards by the 709 so that they can be fed into the Jupiter program. The printout of the Jupiter program will

then contain the output of the merge program, minus the Julian day number, and in addition the merged listening period beginning and end in System III longitude, the merged activity period beginning and end in System III longitude, and a merged probability histogram table of Florida and Chile data combined.

Gross Statistics 1961

The 1961 apparition began February 1, 1961, and ended February 1, 1962. This is the first time that observations of the decameter radiation from Jupiter have been carried through a complete calendar year. Table 2 summarizes the gross statistics of the 1961 apparition.

The observing period, the number of nights of effective listening, and the number of nights that Jupiter radiation was received were arrived at by considering that monitoring at one station constituted coverage. Notice that the percentage of nights that Jupiter radiation was received tends to decrease with increasing frequency. There are some exceptions to this trend. The 19.7 Mc/s system in Australia employed an extremely high-gain antenna, which may account for the figure of 85 per cent. The 49 per cent value at 15 Mc/s is somewhat low. This is probably due to the fact that the array used with this system is non-steerable; thus, Jupiter is in its beam a relatively short time during each night. The 50 per cent value for 5 Mc/s is doubtful. At this wavelength the listening conditions are extremely bad due to absorption in the earth's ionosphere and

TABLE 2

Gross Statistics 1961

Frequency (Mc/s)	Observing period	Number of nights of effective listening	Number of nights Jupiter radiation received	% of nights Jupiter radiation received
5 c	Apr. 13 - July 19 Aug. 3 - Aug. 17	8	4	50
10 c, a	Mar. 4 - Sept. 15	173	119	69
15 f, c	Mar. 2 - Sept. 15 Oct. 25 - Jan. 30, '62	250	122	49
18 f, c	Feb. 1 - Feb. 1, '62	356	189	53
19.7 a	June 19 - Aug. 30	71	60	85
20 c	Mar. 7 - Oct. 9 Oct. 25 - Nov. 20	230	88	38
22.2 f, c	Feb. 25 - Oct. 14 Oct. 25 - Nov. 28	260	93	36
27.6 f, c	Feb. 1 - Feb. 1, '62	336	34	10
31 f	June 8 - Oct. 25	136	5	4

c: Chile; a: Australia; f: Florida.

interference from stations and static, and the few cases susceptible to analysis give at best poor statistics.

During the 1961 apparition the periods of two-station (Chile and Florida) coverage at the different frequencies were: 15 Mc/s - 3 months, 18 Mc/s - 9 months, 22.2 Mc/s - 7 months, and 27.6 Mc/s - 3 months. During these periods the nightly watches were as nearly simultaneous as ionospheric conditions and the $11^{\circ}5'$ difference in longitude would permit. The majority of the Jovian events were recorded at both stations. Two noise storms are considered as different events if they are separated by more than 8.3 minutes of time, or 5° rotation of Jupiter. Table 3 summarizes the circumstances of the Jovian events which were recorded at one station only when the other station was listening effectively. "Effective listening" means periods during which the equipment is operating, Jupiter is in the antenna pattern concerned, and the station is not blanketed by interference at that particular frequency.

TABLE 3

Circumstances of Events Which Were Recorded at One
Station Only, When the Other Station Was
Listening Effectively

	15 Mc/s	18 Mc/s	22.2 Mc/s	27.6 Mc/s
Events recorded in Florida only:				
Event very weak and/or brief	2	28	10	4
Unexplained	0	1	1	0
Events recorded in Chile only:				
Event very weak and/or brief	16	6	7	1
Unexplained	0	0	0	0

The two unexplained events require comment. On July 31 at the Florida station a strong Jovian storm was detected on 18 Mc/s lasting from 0620 to 0639 U.T. Chile was listening under good conditions and detected nothing. On August 10 at the Florida station a Jupiter event lasting 30 minutes (0330 - 0400 U.T.) was recorded on 22.2 Mc/s, yet there were only two pulses on the Chile pen recording. It seems reasonable to assume that these two events were not detected in Chile due to unusual ionospheric conditions. The values in Table 3 reflect the superior listening conditions in Chile at frequencies of 15 Mc/s and below. Any attempt made to explain the distribution of weak events must take into consideration the characteristics (gain, directivity, steerability) of the antenna systems at the different stations.

Source Studies

1961 Probability Histograms

In contrast to the optical features, which show considerable irregularity in their motions (21), the decameter radio sources on or near Jupiter maintain a constant period of rotation. This period was recently determined to be $9^{\text{h}} 55^{\text{m}} 29^{\text{s}}.35$ (2), which agrees very well with the value $9^{\text{h}} 55^{\text{m}} 29^{\text{s}}.37$, independently arrived at by Douglas (22).

The existence of localized zones of activity on or around Jupiter is demonstrated by the peaks on the histograms in Figures 1 and 2. To construct these histograms, we imagine the planet divided into 5° zones of longitude. The "probability of occurrence"

for each zone is the fraction of observing time during which radiation was received while any part of that zone was on the central meridian of the planet.

Figure 1 is a composite of the histograms constructed from data taken in Florida during the 1961 apparition of Jupiter. The letters A, B, and C on the 18.0 Mc/s plot are source designations. The fact that the main peaks on the histograms are less than 180° wide is interpreted as evidence for the existence of directional sources located at the longitudes of the peaks. Notice that the peaks become narrower as the frequency increases. Because of the scarcity of radiation at the higher frequencies, the statistics are weak in the 27.6 and 31.0 Mc/s histograms. Notice also that source B always appears to be broadened. The sources appear to shift position with a change in frequency. As an example of this drift, note how source A is displaced towards lower longitudes as the frequency increases.

Figure 2 is a composite of the histograms constructed from Chile data taken in 1961. Again A, B, and C are source designations and the data used in arriving at the 27.6 Mc/s histogram are sparse. There were cases in 1961 of reception of Jovian radiation at 5 Mc/s in Chile; however, the data were not sufficient to justify plotting a histogram. Again the same features are found by examining the Chile histograms: the peak widths are less than 180° , the peak width decreases as the frequency increases; source B appears broadened; and as the frequency increases, the peaks are displaced towards lower longitudes. The 10.0 Mc/s histogram is difficult to interpret because of the broadening of the sources at the lower frequency. It is reasonable to

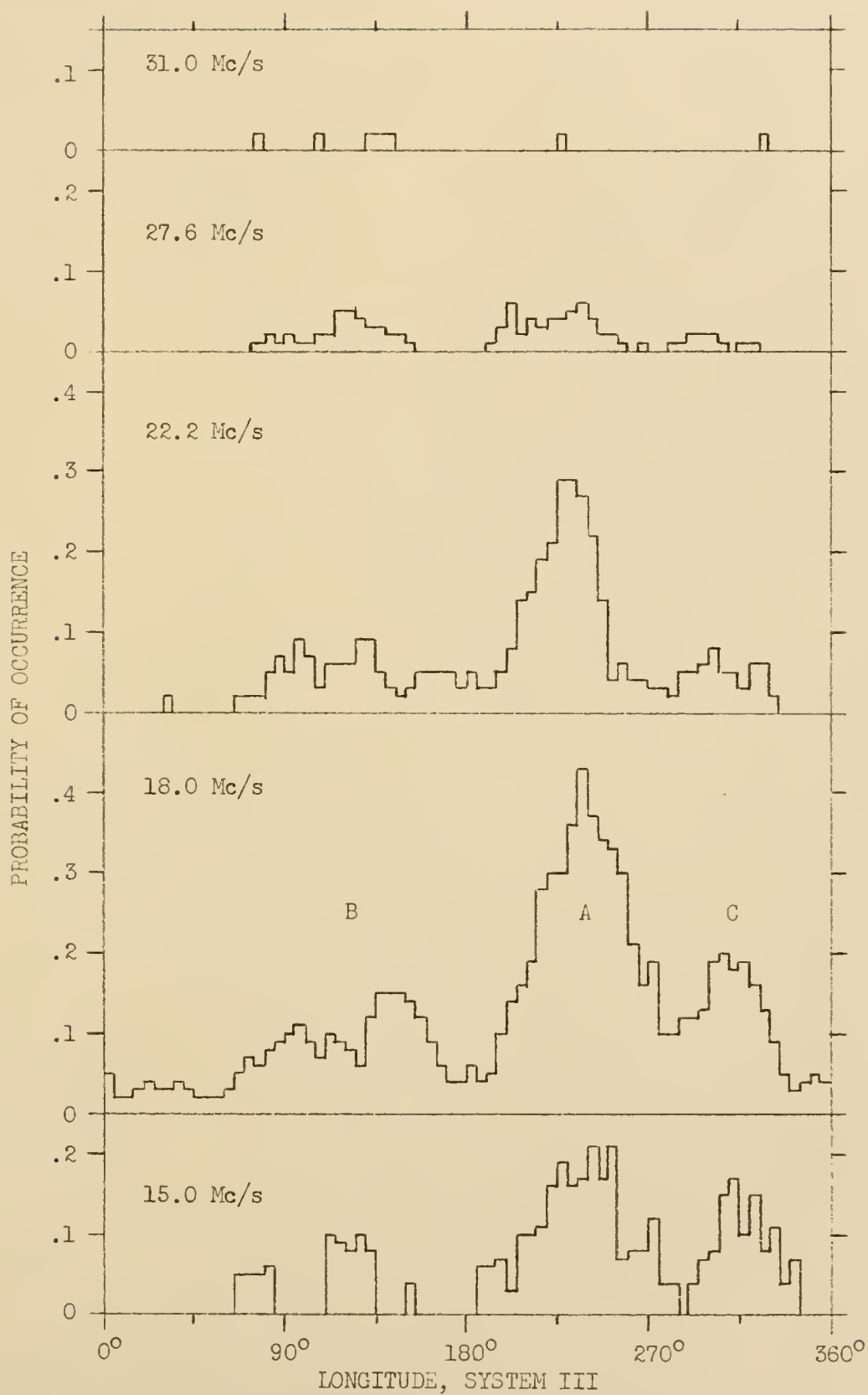


Figure 1.--Histograms of the Florida 1961 data.



Figure 2.--Histograms of the Chile 1961 data.

assume that the main source A extends from 266° to 36° , as will be pointed out later in the text.

Three degrees of certainty are used by observers on watch in identifying Jovian radiation: "positive," "possible," and "dubious." In constructing our histograms, only the "positive" and "possible" Jupiter radiation is used. As a check on the authenticity of the "possible" identifications, a histogram of the Florida 18 Mc/s "positive data" has been generated and, in Figure 3, it is compared with the regular 18 Mc/s Florida histogram. All features of importance on the "positive data" histogram are plainly evident on the regular histogram; hence, it is concluded that inclusion of the "possible" identifications is not diluting the good data.

Merging the Data from Different Stations

During 1960 and 1961 Jupiter radiation was monitored on several frequencies which were used at two observing stations. This not only provides a check on our data, but also makes it possible to determine whether or not there are any lasting station effects such as better resolution with the antenna system at one station, shifts in the peaks on our histograms, or better atmospheric conditions characterized by superior reception at one of the stations. All of the histograms have been "smoothed" by taking a 3-point running average, i.e., averaging the probability value for each 5° increment of longitude with the value preceding it and the value following it. This "smoothing," as the name implies, removes much of the bumpiness evident in the histograms of Figures 1 and 2. The following figures contain

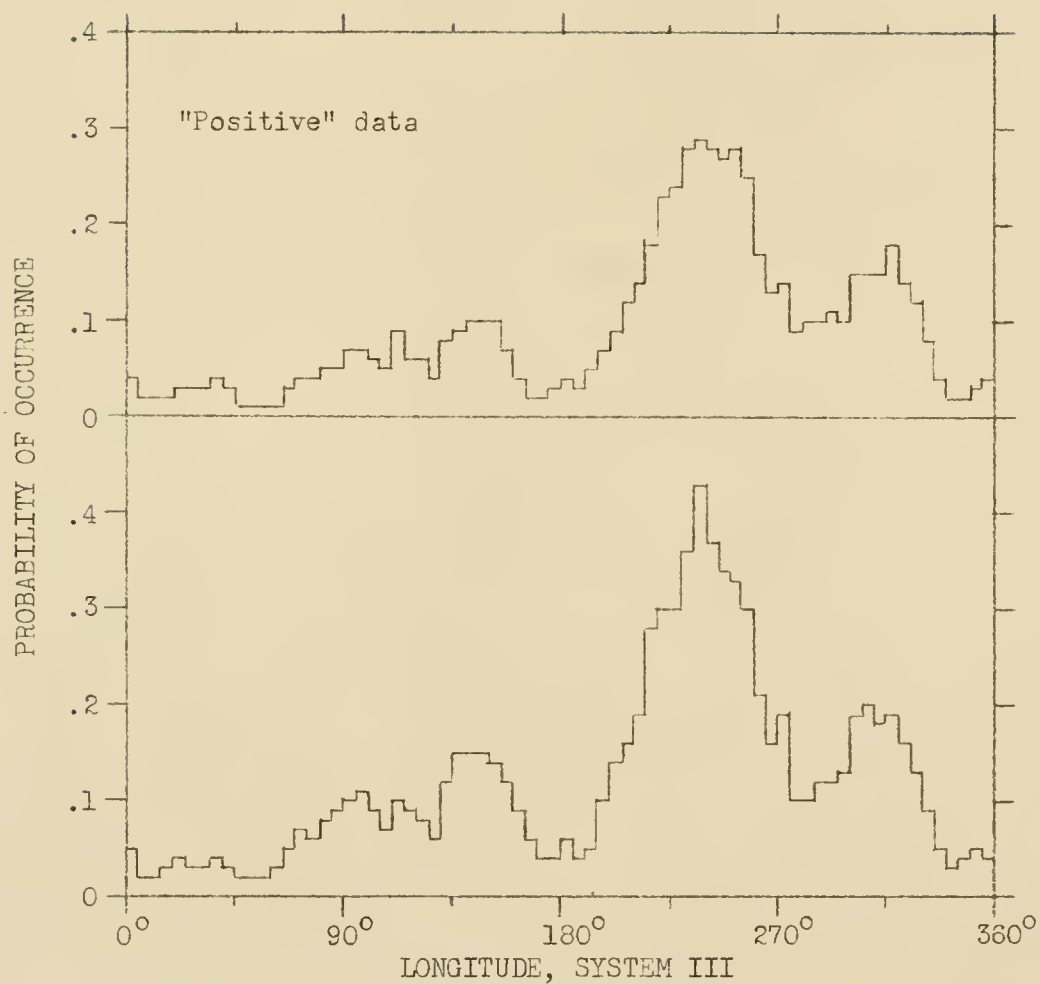


Figure 3.--1961 histograms of the 18 Mc/s Florida data. The "possible" identifications of Jovian noise were not included in the data used to construct the upper histogram.

single-station histograms above and a merged histogram, which is the result of combining the data of the two stations, below. See the explanation earlier in this chapter of the merge program for the 709.

Figure 4 contains 10 Mc/s histograms of the 1961 data. The Australian histogram comes from data taken by Professor T. D. Carr during June - August, 1961, at an observing station near Sidney. The 10 Mc/s antenna systems at the Chile and Australian stations are identical, hence the slight splitting of the peak representing source B is assumed due to the statistical fluctuations in the data. Considering the broadening of the peaks at the lower frequencies, it is felt that the upper two histograms are very well correlated. The higher probability values associated with the Australian histogram reflect the better listening conditions at that station due to less atmospheric noise and a generally less dense night-time ionosphere (23). The merged histogram in Figure 4 results from a combination of the Chile and Australia data, and it is felt that this plot gives the best picture yet obtained of the source structure at 10 Mc/s.

Figure 5 contains 15 Mc/s histograms of the 1961 data. The fact that source B shows more splitting on the Florida histogram must be due to scatter in the data. Again the higher probability values reflect better listening conditions in Chile. It is noteworthy that Jupiter was more nearly overhead in Chile during the 1961 apparition. More data were available from which to construct the Chile histogram because the antenna system is electrically steerable, providing longer observing periods. The merged histogram gives the best representation of the 1961 15 Mc/s data.



Figure 4.--10 Mc/s histograms 1961.

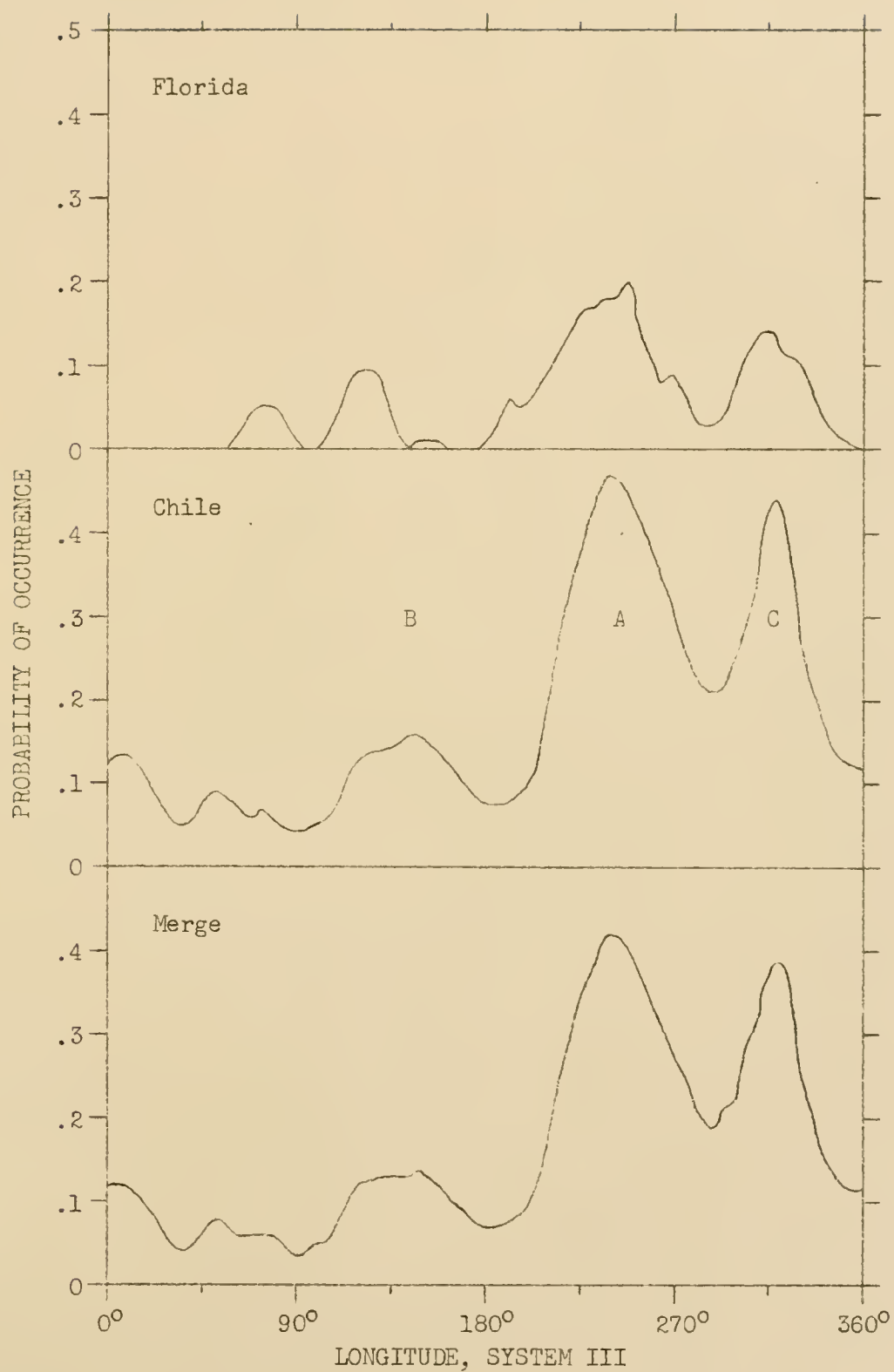


Figure 5.--15 Mc/s histograms 1961.

Figure 6 contains the 18 Mc/s histograms constructed from the 1961 data. The correlation between Florida and Chile is excellent. Figure 7 and Figure 8 represent the 22.2 and 27.6 Mc/s data respectively. In all cases the histogram correlation between stations is good, and it does not appear that any station effects are being disguised by merging the data. (Notice that the small bump on source C in Figure 7 disappears in the merge. This is due to the round-off procedure of the 709 program, which calculates the probability values to the nearest 0.01.)

Figure 9 compares the Chile 20.0 Mc/s and the Australian 19.7 Mc/s histograms, both constructed from the 1961 data. There is no merged histogram in this case because the frequencies are not the same. Any effects such as the longitude shift of the peaks with frequency and the narrowing of the peaks with increasing frequency would have been hidden by merging the data. The frequencies are sufficiently close that a comparison seems worthwhile, and the correlation is quite good. It should be remarked that the 19.7 Mc/s system in Australia possesses very high gain.

The first year that the Jovian decameter emission was monitored simultaneously in Chile and Florida was 1960; thus, for the sake of completeness, the 1960 station merged histograms are included here. They have been constructed by the 709 computer using the corrected System III rotation period. Figures 10 and 11 contain the 18 Mc/s and 22.2 Mc/s histograms of 1960. The Florida and Chile histograms of both figures are well correlated. There is one feature, however, which



Figure 6.--18 Mc/s histograms 1961.

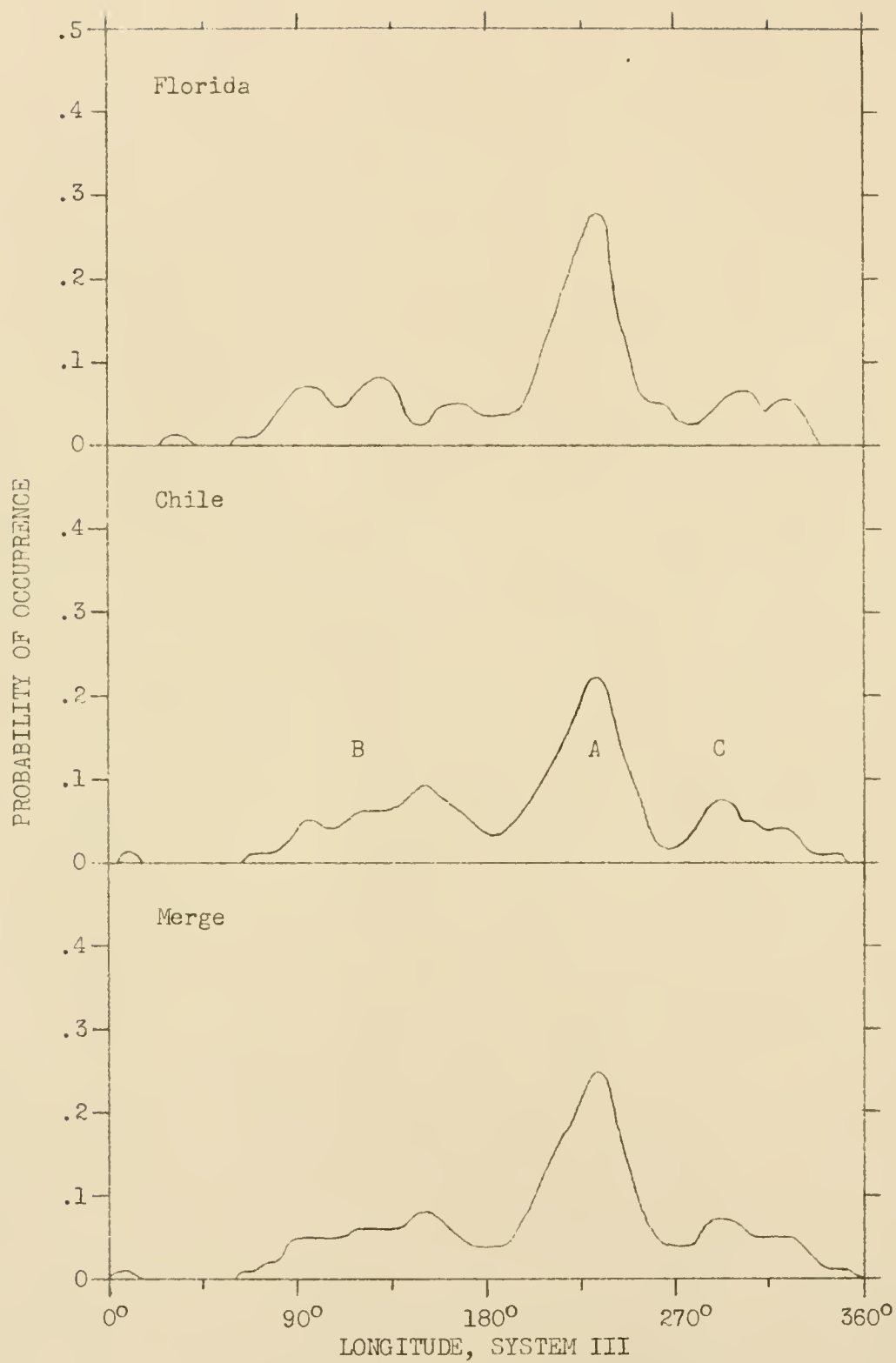


Figure 7.--22.2 Mc/s histograms 1961.

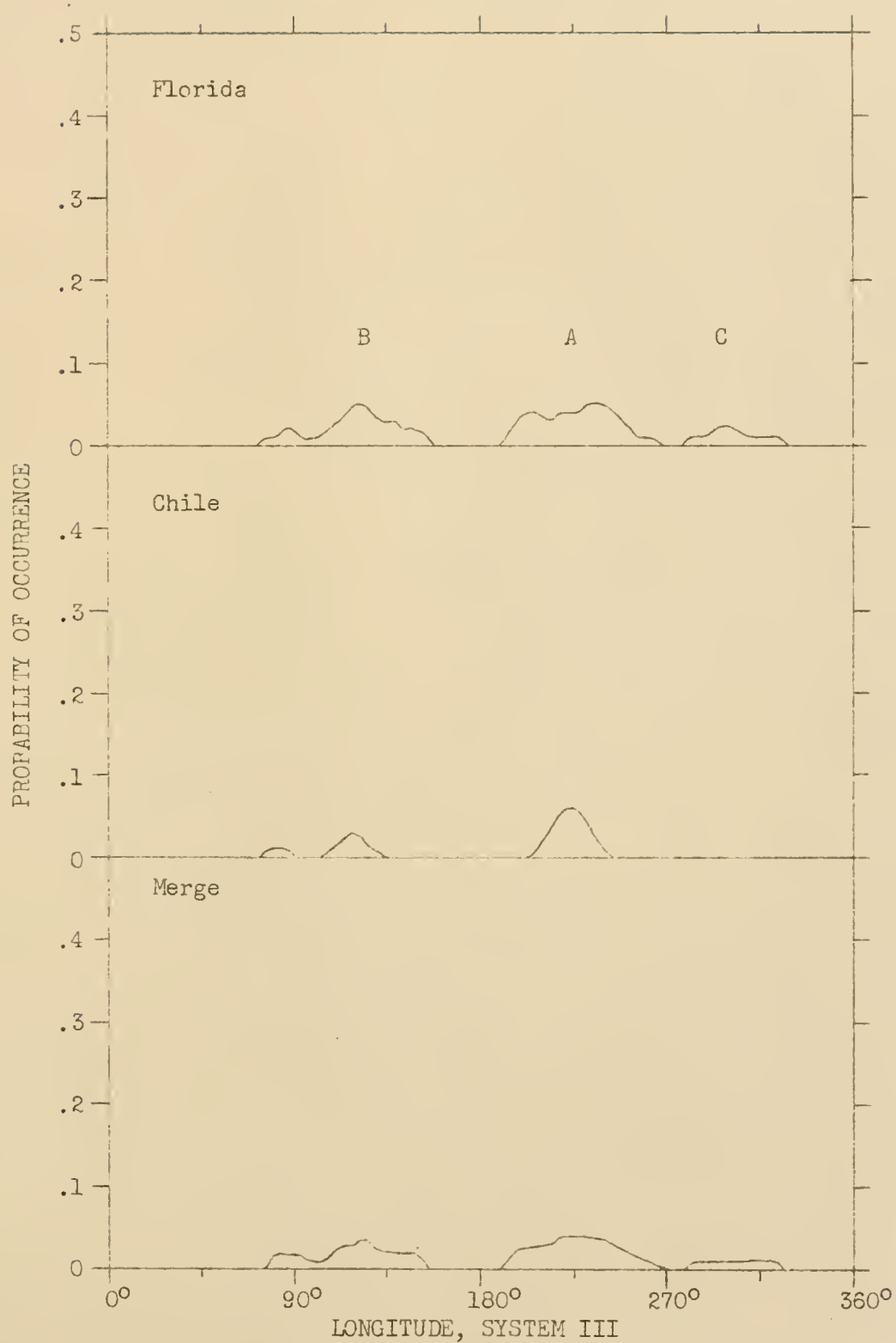


Figure 8.--27.6 Mc/s histograms 1961.

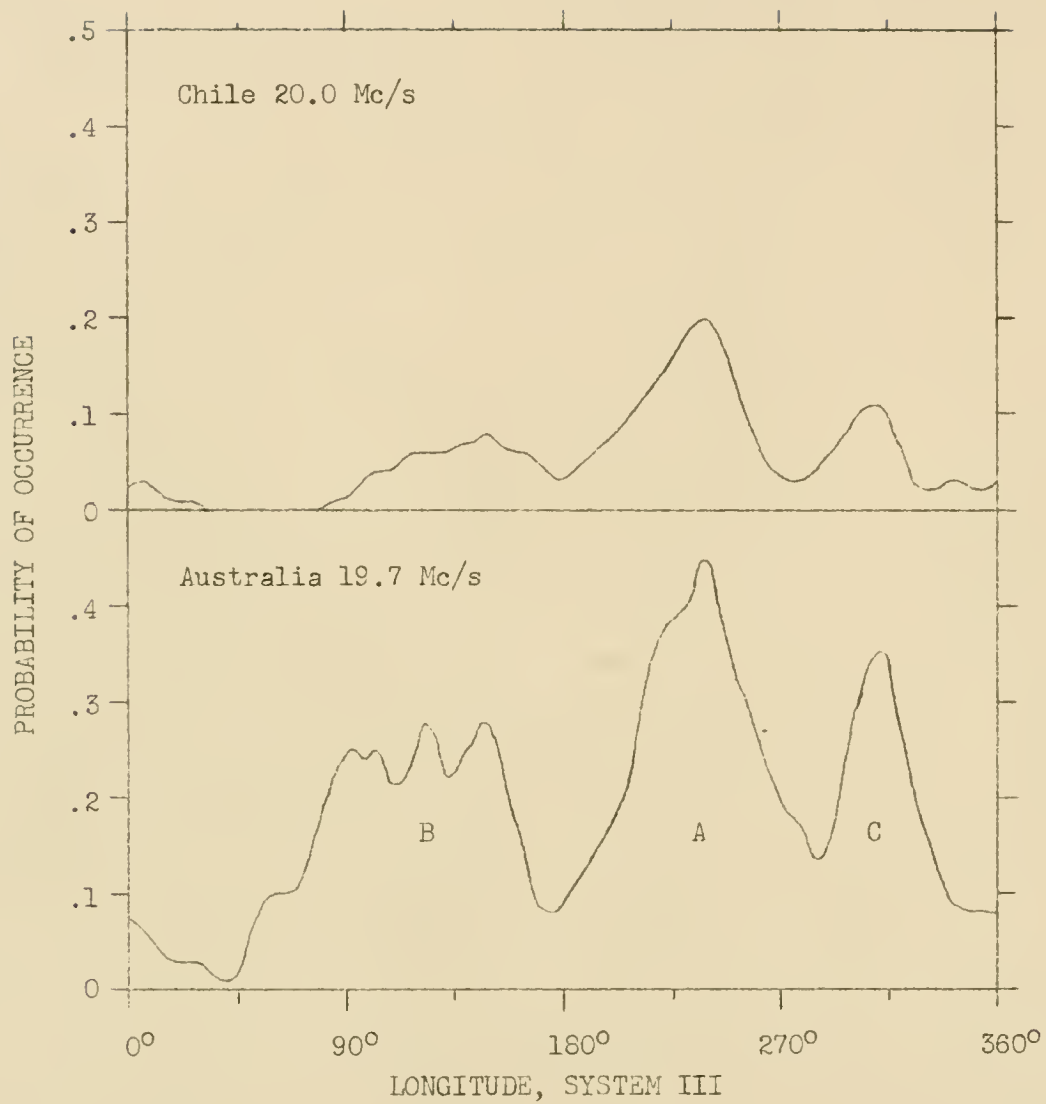


Figure 9.--20.0 and 19.7 Mc/s histograms 1961.

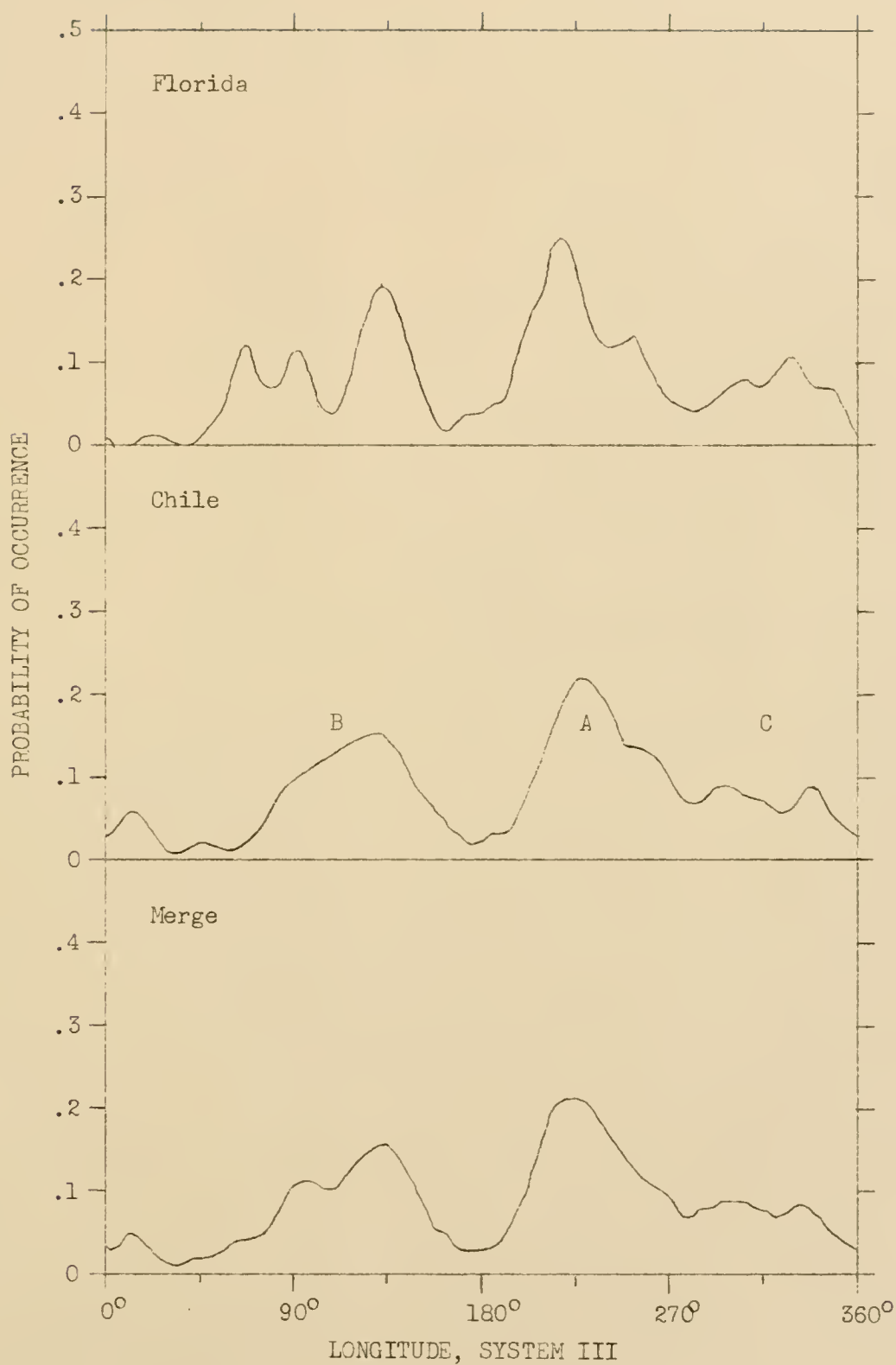


Figure 10.--18 Mc/s histograms 1960.



Figure 11.--22.2 Mc/s histograms 1960.

deserves mentioning. On both the 18 Mc/s and 22.2 Mc/s Florida histograms, source B appears split, having three maxima on the 18 Mc/s curve and two on the 22.2 Mc/s curve. This splitting does not show up on either of the Chile histograms. Considering antenna patterns and observing conditions at the different stations, I cannot think of an explanation for this feature; hence, it is concluded that the effect is not a real character of the Jovian radiation, but rather a consequence of scatter in the data. Again the merged histograms provide the best picture of the source distribution.

Search for Long-Term Changes

Having concluded that there are no significant station effects, a comparison is made in this section of single frequencies over a span of years using the smoothed histograms and the smoothed merged histograms to determine whether or not there is evidence of any long-term change in the activity of the different sources.

Figure 12 shows the 10 Mc/s histograms for 1960 and 1961. The 1960 apparition in Chile was our first attempt to obtain Jovian signals at a frequency as low as 10 Mc/s, and not much data was obtained. With the sunspot activity on the decline and the earth's ionosphere becoming more transparent to the lower frequencies, a large amount of data was collected on 10 Mc/s during 1961. Notice that Jupiter seems much more active at 10 Mc/s in 1961 than in 1960.

Comparison of the two histograms in Figure 12 reveals the same general source structure. The 1961 merged histogram shows sources B

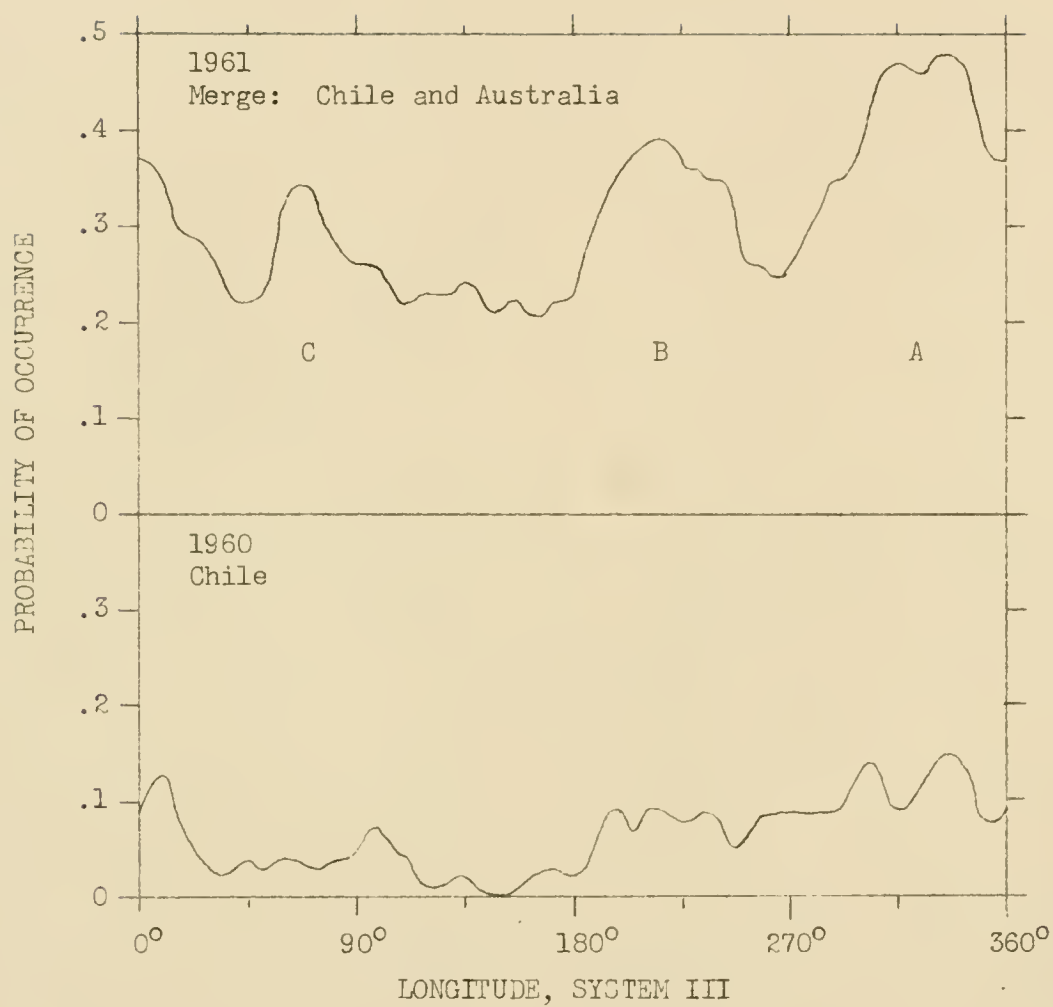


Figure 12.--10 Mc/s histograms.

and C more developed. It is interesting to note that source A is bifurcated on the 1960 plot and also slightly on the 1961 plot.

Figure 13 contains 18 Mc/s histograms covering a six-year span. The data used to generate the 1956 histogram are those of R. M. Gallet (24), taken at the National Bureau of Standards, Boulder, Colorado, during the period January - March 1956. The shape of this histogram conforms well with that of a histogram constructed from data collected by K. L. Franklin and B. F. Burke (25) in 1956 on 18.5 Mc/s. This latter histogram is not included here because of the difference in frequency. The remaining five histograms in Figure 13 are those of the Florida group. Most noticeable is the decrease in activity during 1958 and 1959 accompanying sunspot maximum. Source A is the most prominent peak on each year's histogram. B appears to be the broadest peak, except in 1958 and 1959 when there was little activity. Source C started out in 1956 more active than B. In 1960, C was surpassed by B, but during the 1961 apparition C regained the lead. The breadth of source B may be an indication that there are two closely spaced sources, and in some cases the separation on the histograms may be evidence of resolution. Notice this on the curves of 1956, 1960, and 1961. This feature will be commented upon later in the text.

The center of source A is marked on each of the histograms at one-half maximum height. No consistent drift is apparent; however, a certain amount of randomness shows. On the 1961 histogram a shift to the right is evident. A plausible explanation of this effect will be discussed later on. Again, be reminded that the data taken in 1958 and 1959 were thinly scattered.

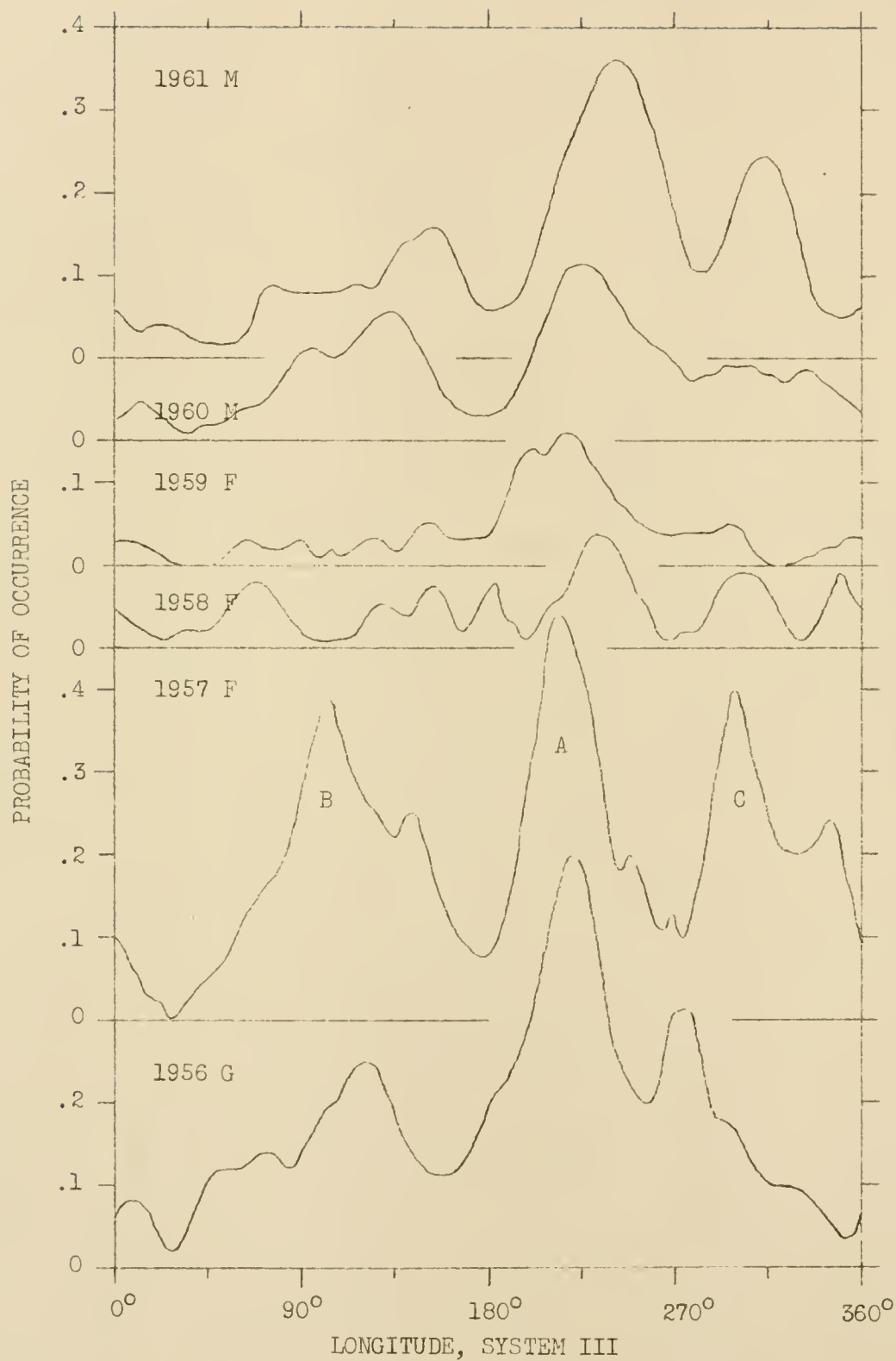


Figure 13.--18 Mc/s histograms. Legend: F - Florida, G - Gallet, M - Merge.

Figure 14 contains three 20 Mc/s histograms. Gallet's data were taken from reference 24. There being no continuity from 1956 to 1960, it is only possible to infer from the data at other frequencies that the 20 Mc/s activity declined during the period of sunspot maximum. A is the most prominent source and B again appears broadened. Notice that source C was less active than B at 20 Mc/s in 1956. The reverse held true at 18 Mc/s. The 1961 histogram shows C more active than B. Again the peaks in the 1961 histogram are shifted to higher longitudes.

Figure 15 contains 22.2 Mc/s histograms covering 4 consecutive years. The activity is at a low in 1959 as signified by the smaller values of probability. Once more, A is the most prominent; B appears broad, suggesting a combination of sources on the 1958 and 1960 curves; and source A is shifted to the right on the 1961 histogram. At 22.2 Mc/s, source C is very insignificant.

Figure 16 contains 27.6 Mc/s histograms for 1959, 1960, and 1961. The probability of receiving decameter wavelength radiation from Jupiter falls off with increasing frequency. This is well illustrated by the small ordinate values in Figure 16. The 1959 data were very meager. Notice that source C disappeared in 1960. There is some evidence in 1960 and 1961 of splitting of source B. Any conclusions based upon the 27.6 Mc/s curves must be regarded with caution because of the small amount of activity they were derived from.

In order to see if there were any short-term changes in the activity of the different sources, several sets of monthly histograms were generated on the computer. At none of the frequencies investigated

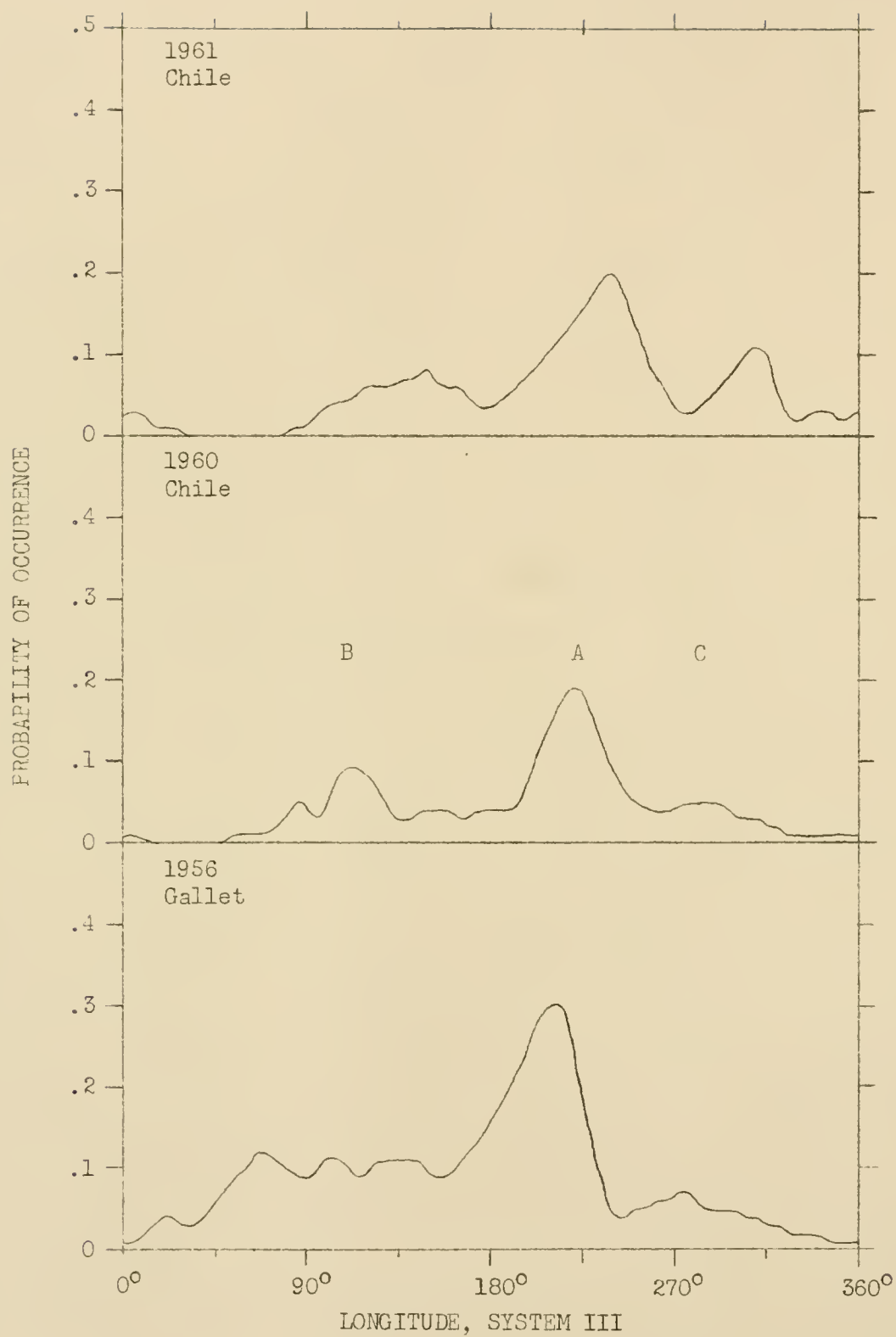


Figure 14.--20 Mc/s histograms.

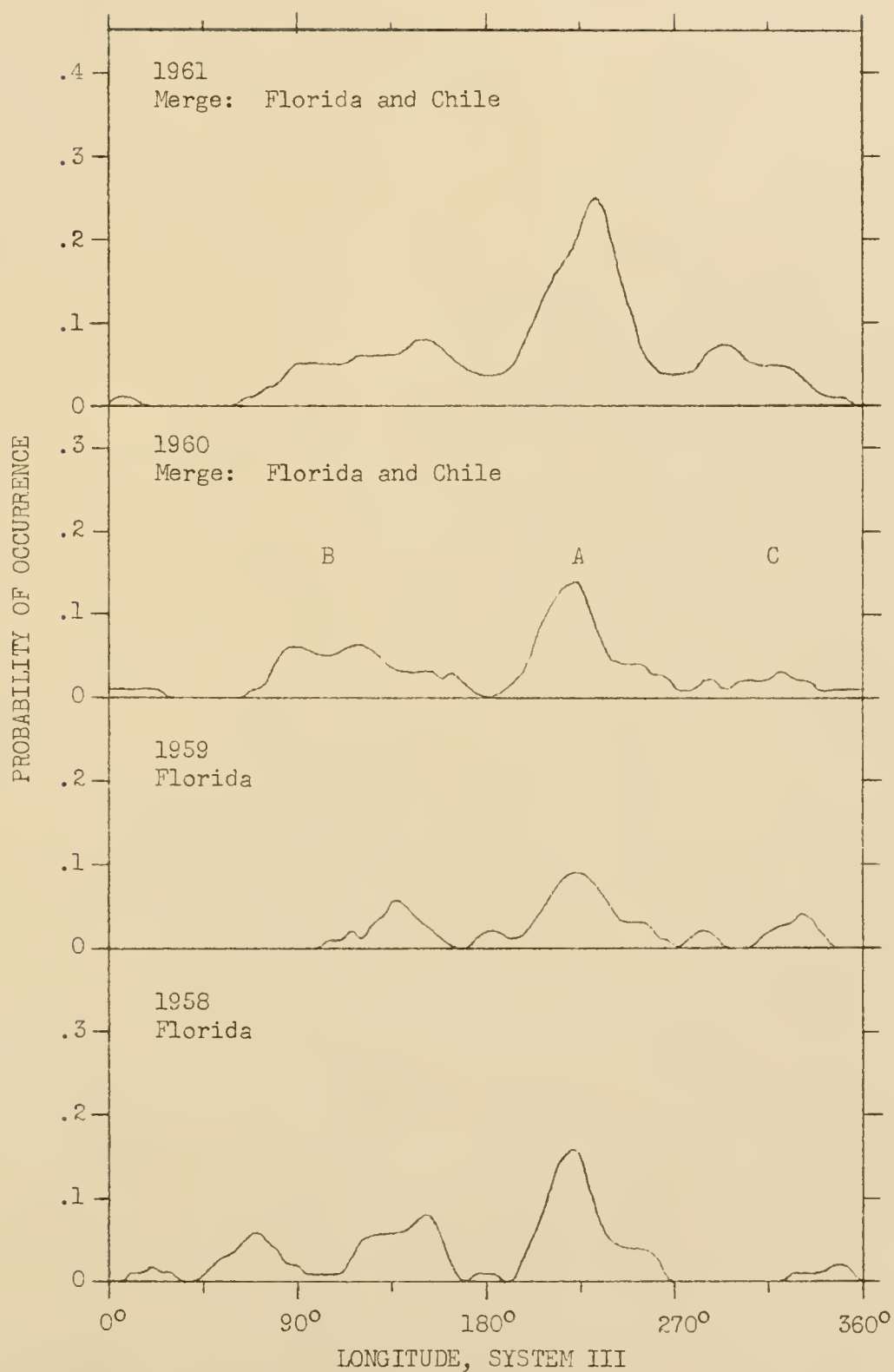


Figure 15.--22.2 Mc/s histograms.

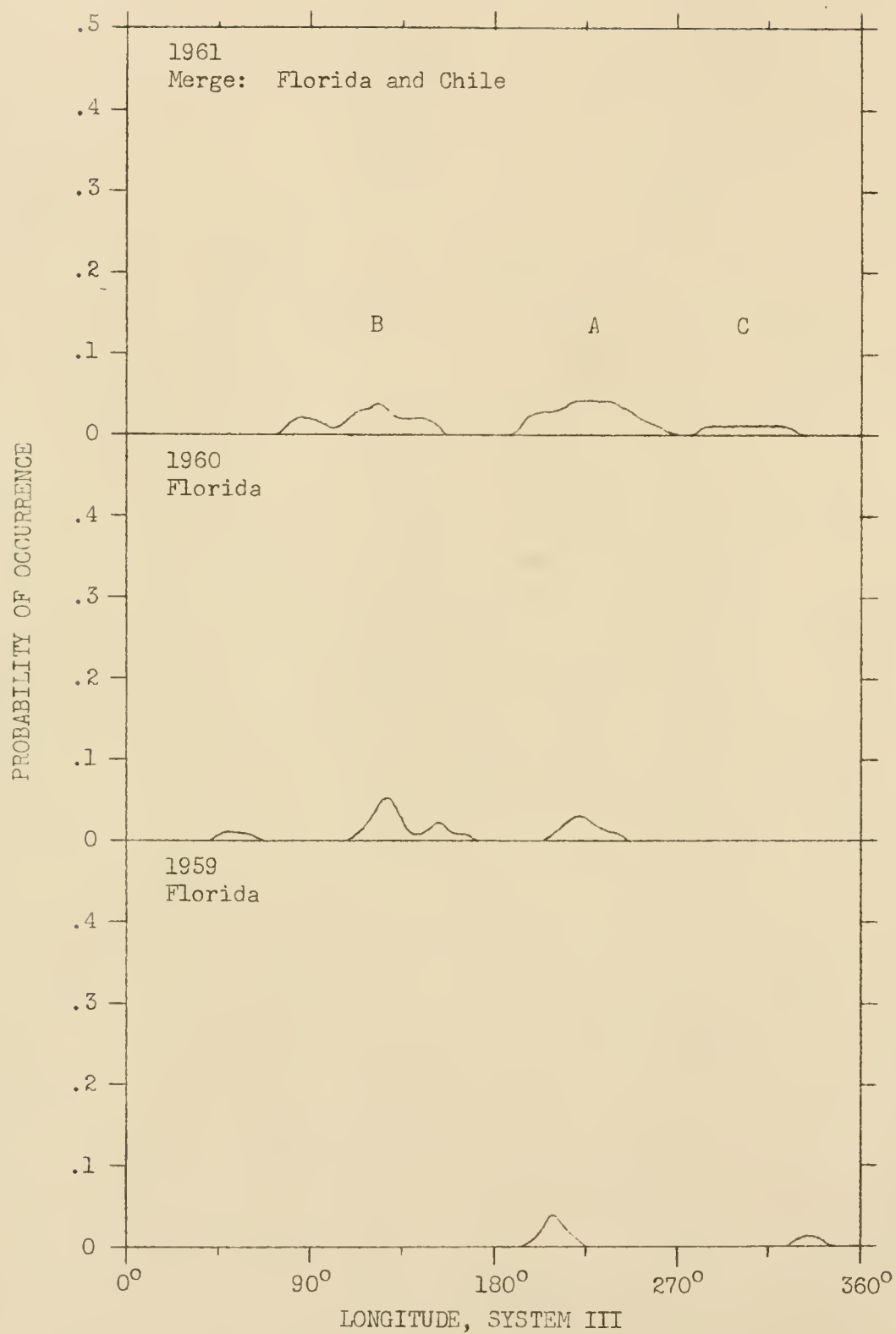


Figure 16.--27.6 Mc/s histograms.

did the activity show any pattern of shifts from one source to another on these monthly histograms.

In conclusion, the following can be said about the search for changes in the source structure from year to year. Most of the prominent features on the histograms remain unchanged. Source A is the most prominent. Source B is broad and appears split in many cases. But, two effects have been discovered.

1. The activity of source C varies from year to year in comparison with B.
2. Source A is shifted towards higher longitudes in 1961.

Search for Station Effects

It was concluded earlier that by merging the data obtained on a single frequency but at two different stations, no effects that characterized the decameter sources were being covered up. In order to subject this conclusion to further test, a comparison is made of histograms obtained by combining the data of different apparitions but not merging the data from separate stations. In so doing, the two effects discovered in the previous section will be masked, but we will remember that they do exist. The prominent features of the source structure will not be altered by this treatment of the data. One question posed earlier should be answered by this examination. Does source B show more splitting on the Florida histograms?

Figure 17 contains two 10 Mc/s histograms, one a combination of data taken during two apparitions in Chile, and the other constructed from data obtained during a 2 1/2-month period in Australia. The



Figure 17.--10 Mc/s histograms, data of different years combined.

general source structure is the same on the two curves. The slight splitting of source B on the Australian histogram has been noticed on the histograms in preceding sections.

Figures 18, 19, and 20 compare Florida histograms representing the data of several apparitions with Chile histograms of data taken in 1960 and 1961. The correlation in each figure is extremely good. The probability values are about equal at the different stations. The amount of radiation received from the separate sources is the same in Chile and Florida. There appears to be no displacement of peaks between stations. And in answer to the question posed, source B has the same structure on the Florida and Chile histograms at each of the three frequencies at which a station comparison is made. Hence we conclude once again that there are no station effects in the data which alter the histogram structure.

Combining the Data of Different Apparitions and Different Stations

In order to obtain the most reliable picture possible of the source structure at each frequency, all the data that have been collected by the Florida group since 1957, including that taken in Chile and Australia, have been combined to produce the histograms in Figures 21 through 26. The only effect we are hiding by lumping together the data of different apparitions is the shift of source A to slightly higher longitudes on the 1961 curves at 18 Mc/s, 20 Mc/s, and 22.2 Mc/s. The result of combining the 1961 data with that of the other years will be a broadening of source A at these three frequencies and a slight shift of the center of A toward higher longitudes.

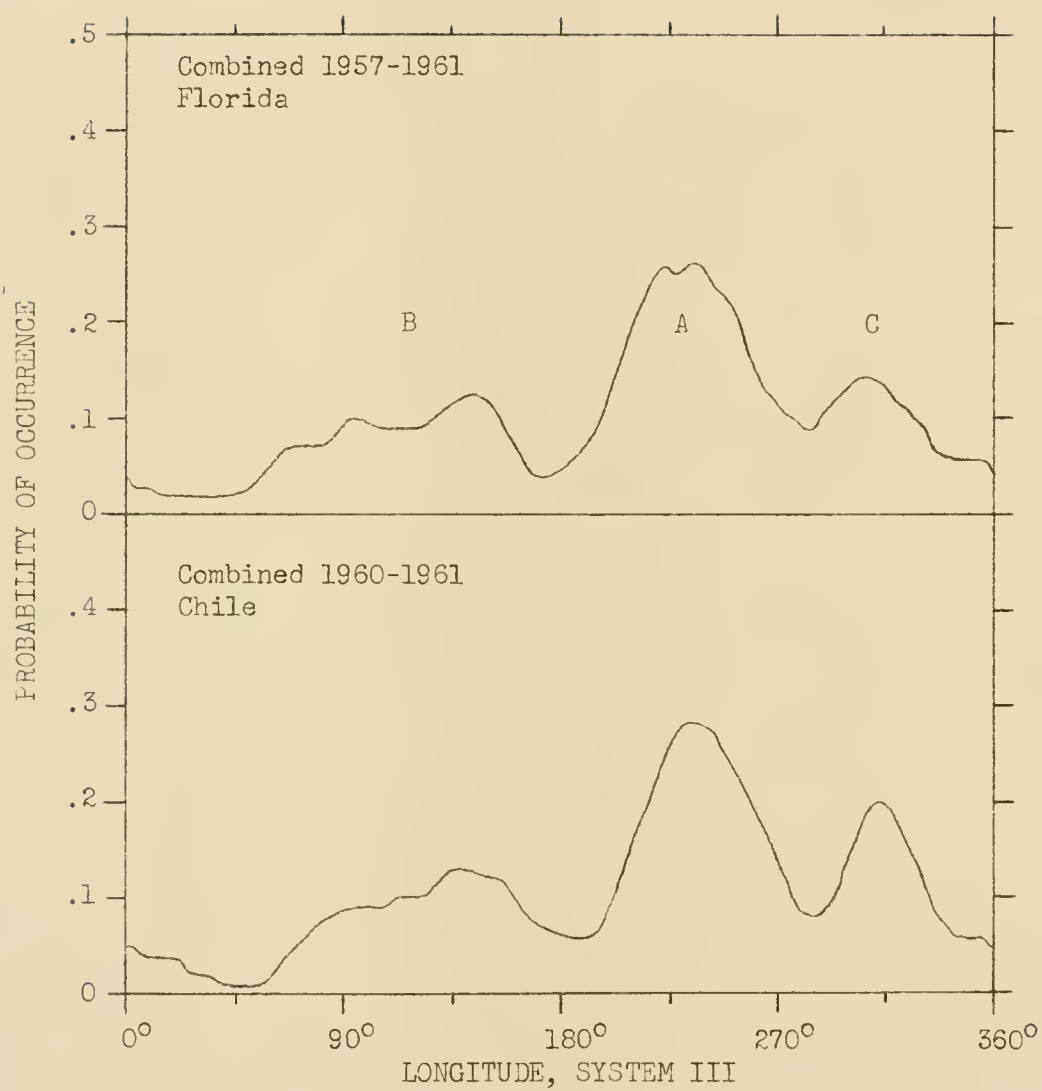


Figure 18.--18 Mc/s histograms, data of different years combined.

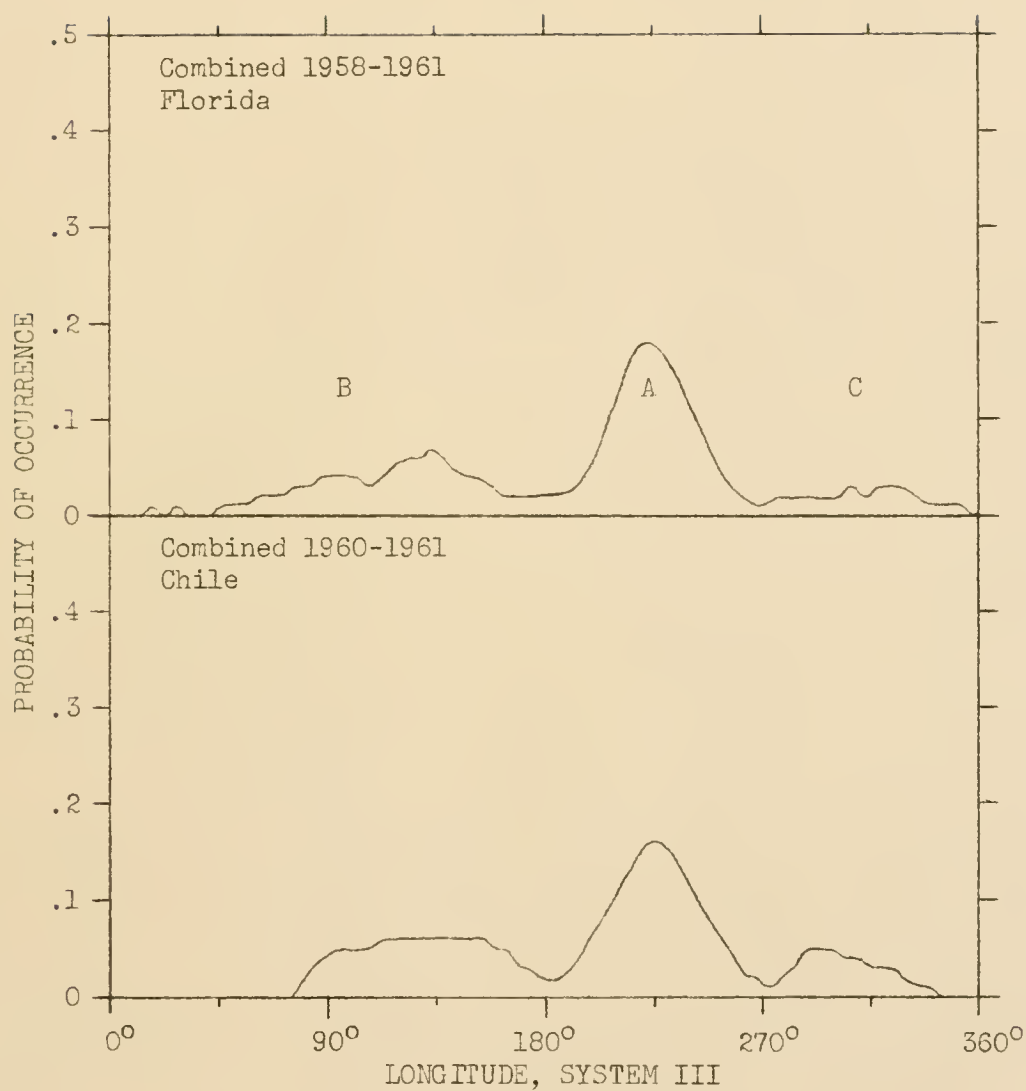


Figure 19.--22.2 Mc/s histograms, data of different years combined.

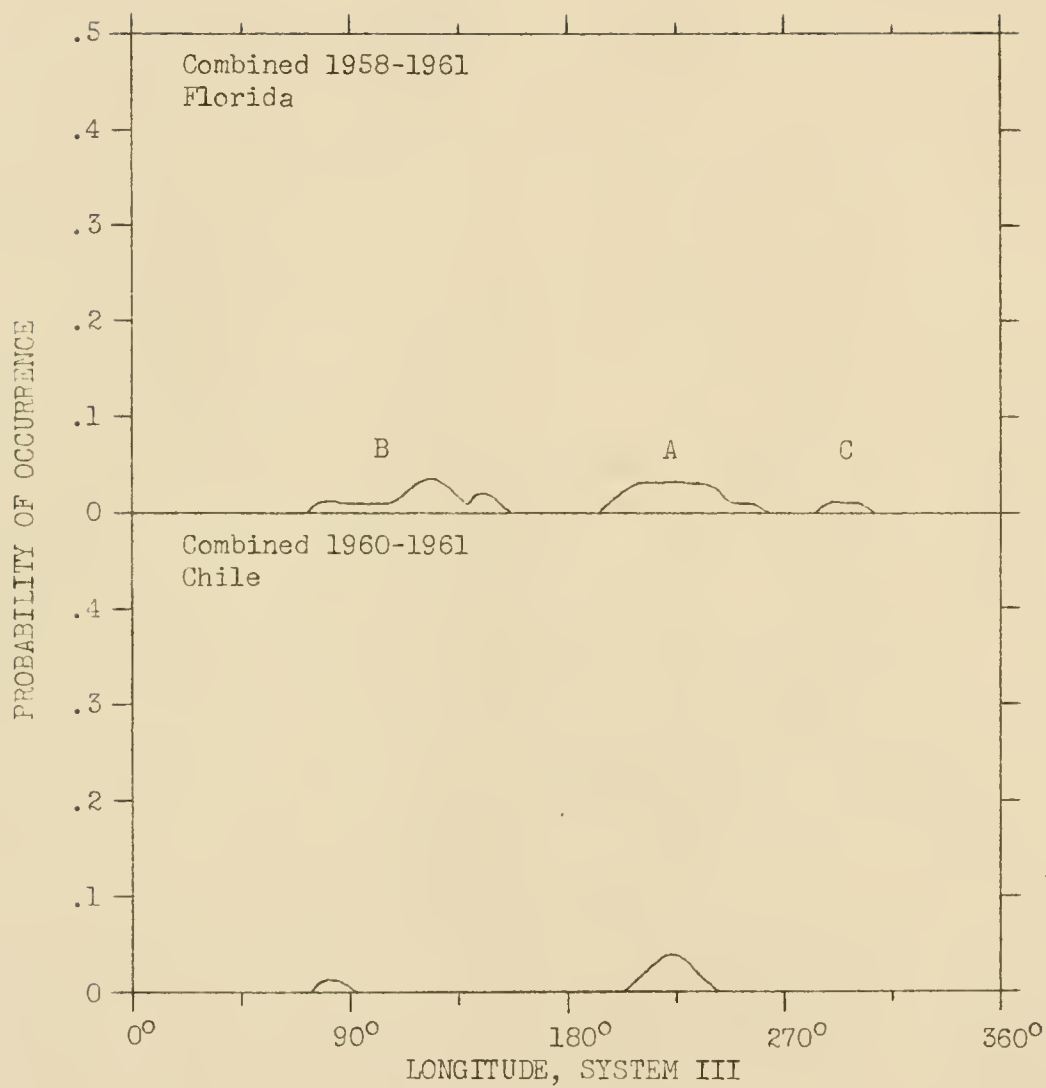


Figure 20.--27.6 Mc/s histograms, data of different years combined.

Conclusions Regarding Number, Location, Separation,
and Width of the Sources

By inspection of Figures 21 through 26, three main sources, A, B, and C, can be clearly identified, and there is a suggestion of splitting of source B on the 18 Mc/s, 20 Mc/s, and 22.2 Mc/s histograms. It is possible that this broad peak represents two closely spaced sources which are only partially resolved. The existence of four main sources is easier to explain than three. If the sources are connected to the solid core of the planet through its magnetic field, it is possible that two magnetic dipoles are involved.

The source structure does not vary much from frequency to frequency. The most change occurs in source C, which shrinks away to nothing at 27.6 Mc/s, yet at 18 Mc/s it is more active than source B, and at 15 Mc/s it is on a par with source A.

Table 4 gives the location of sources A, B, and C in System III longitude and the widths of the histogram peaks at one-half maximum height. These measurements were taken on Figures 21 through 26.

TABLE 4
Location and Width of the Decameter Sources
from the Merged Histograms

Frequency (Mc/s)	Location of the source center (System III)			Width (degrees)		
	A	B	C	A	B	C
10	330	222	80	135	90	65
15	246	142	312	67	70	46
18	235	120	310	66	100	50
20	228	135	299	52	70	43
22.2	225	127	305	45	90	55
27.6	225	125	302	45	25	20

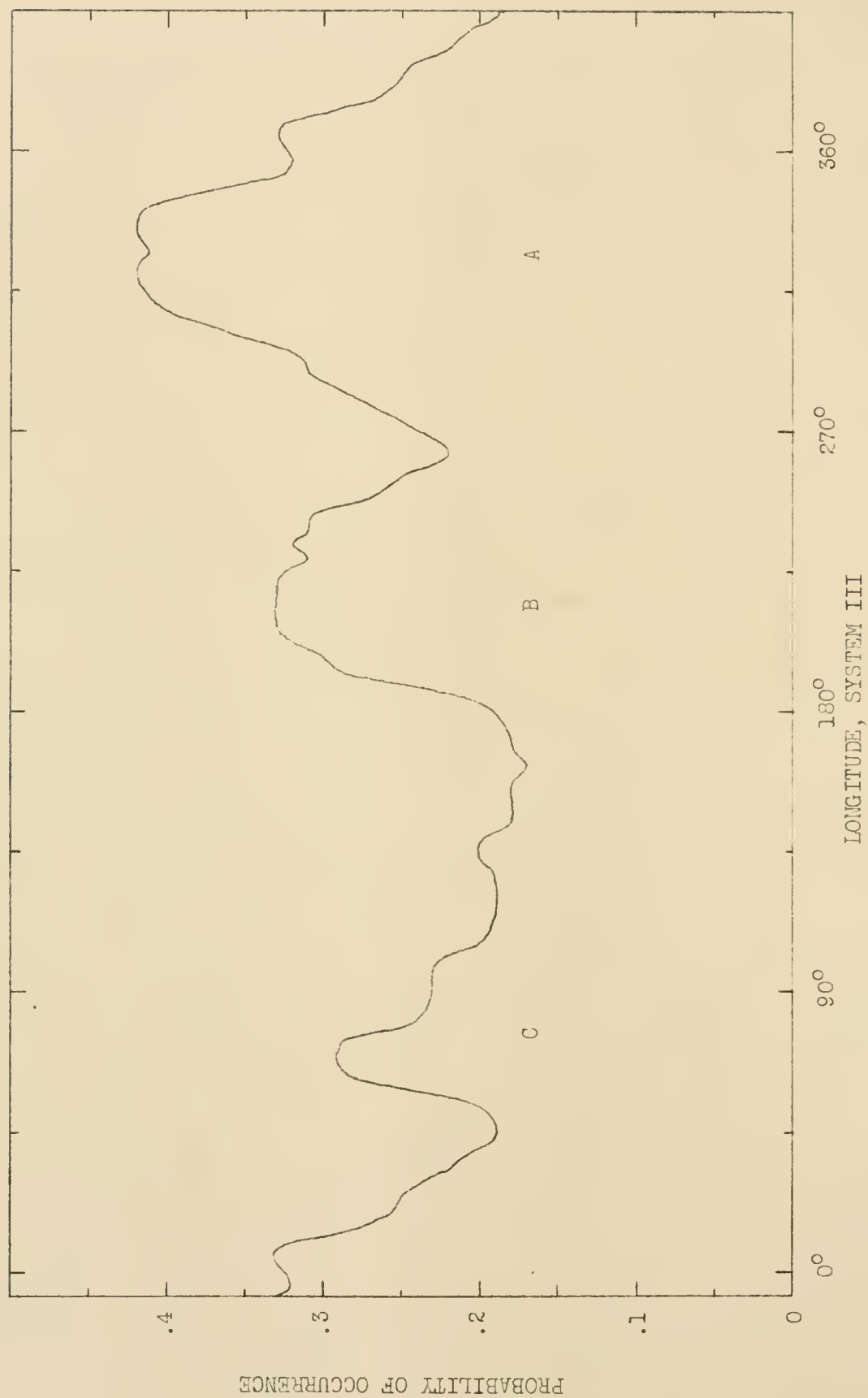


Figure 21.--10 Mc/s histogram of Chile and Australian data 1960-1961.



Figure 22.--15 Mc/s histogram of Florida and Chile data 1961.

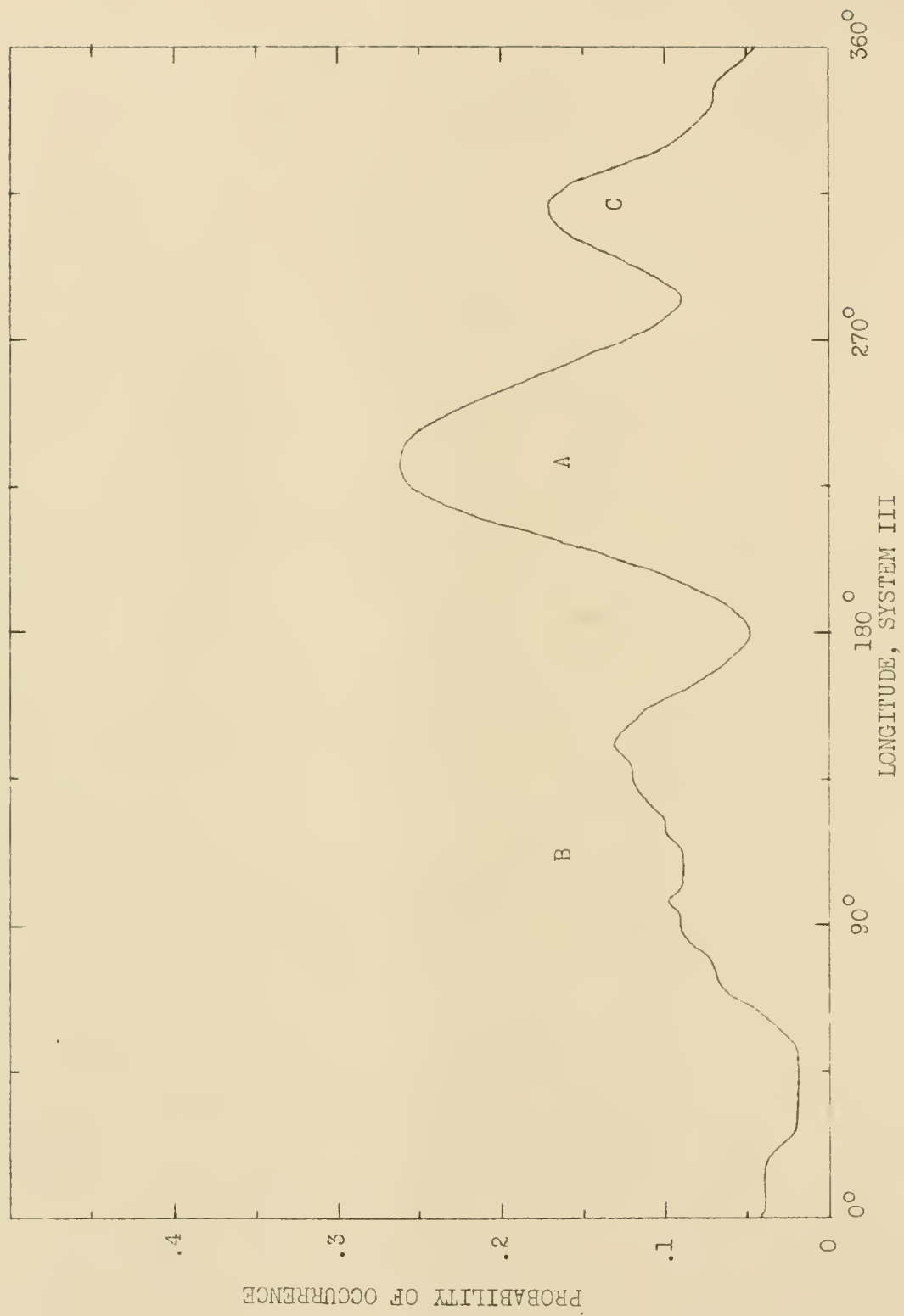


Figure 23.--18 Mc/s histogram of Florida and Chile data 1957-1961.

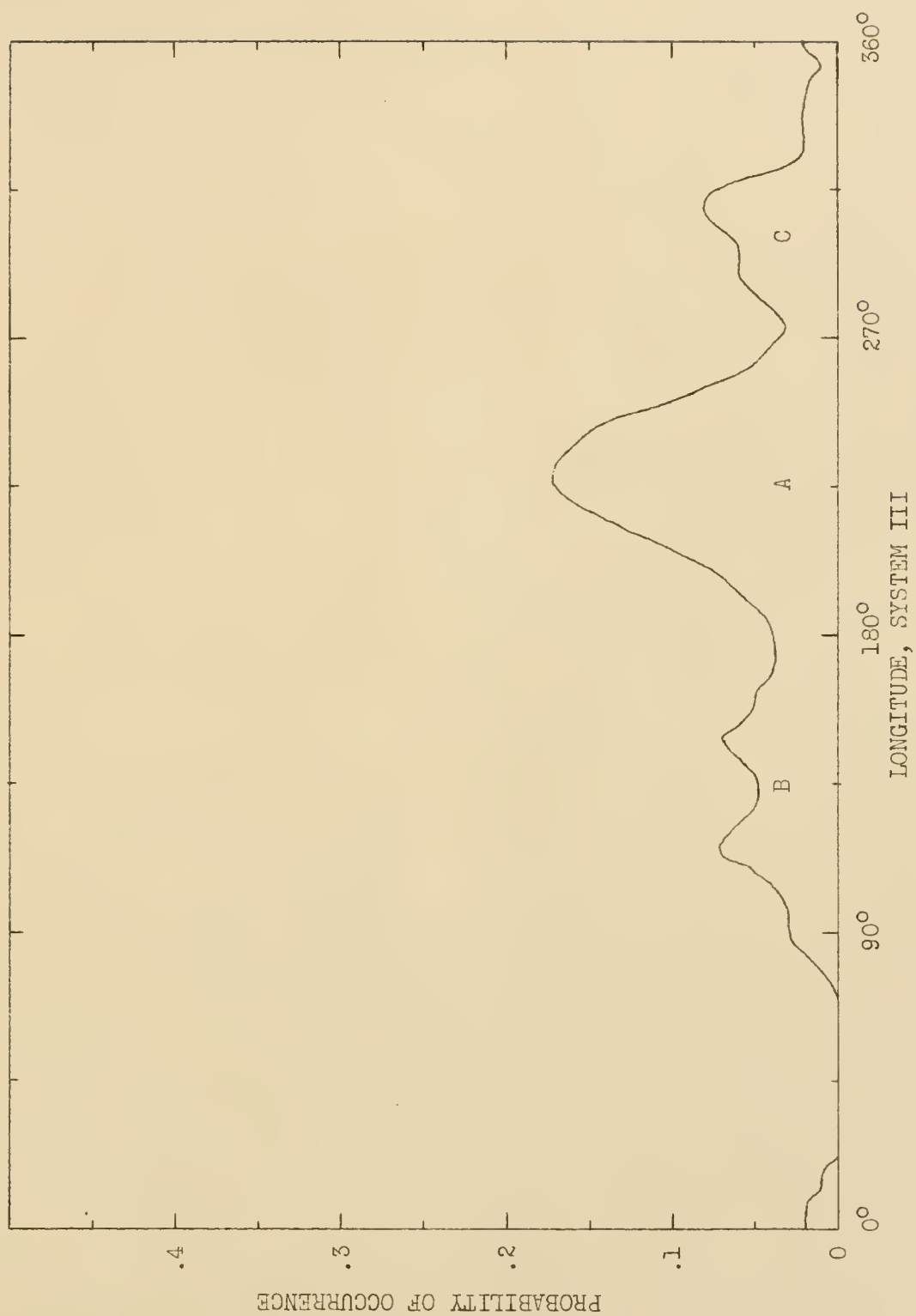


Figure 24.--20 Mc/s histogram of Chile data 1960-1961.



Figure 25.--22.2 Mc/s histogram of Florida and Chile data 1958-1961.

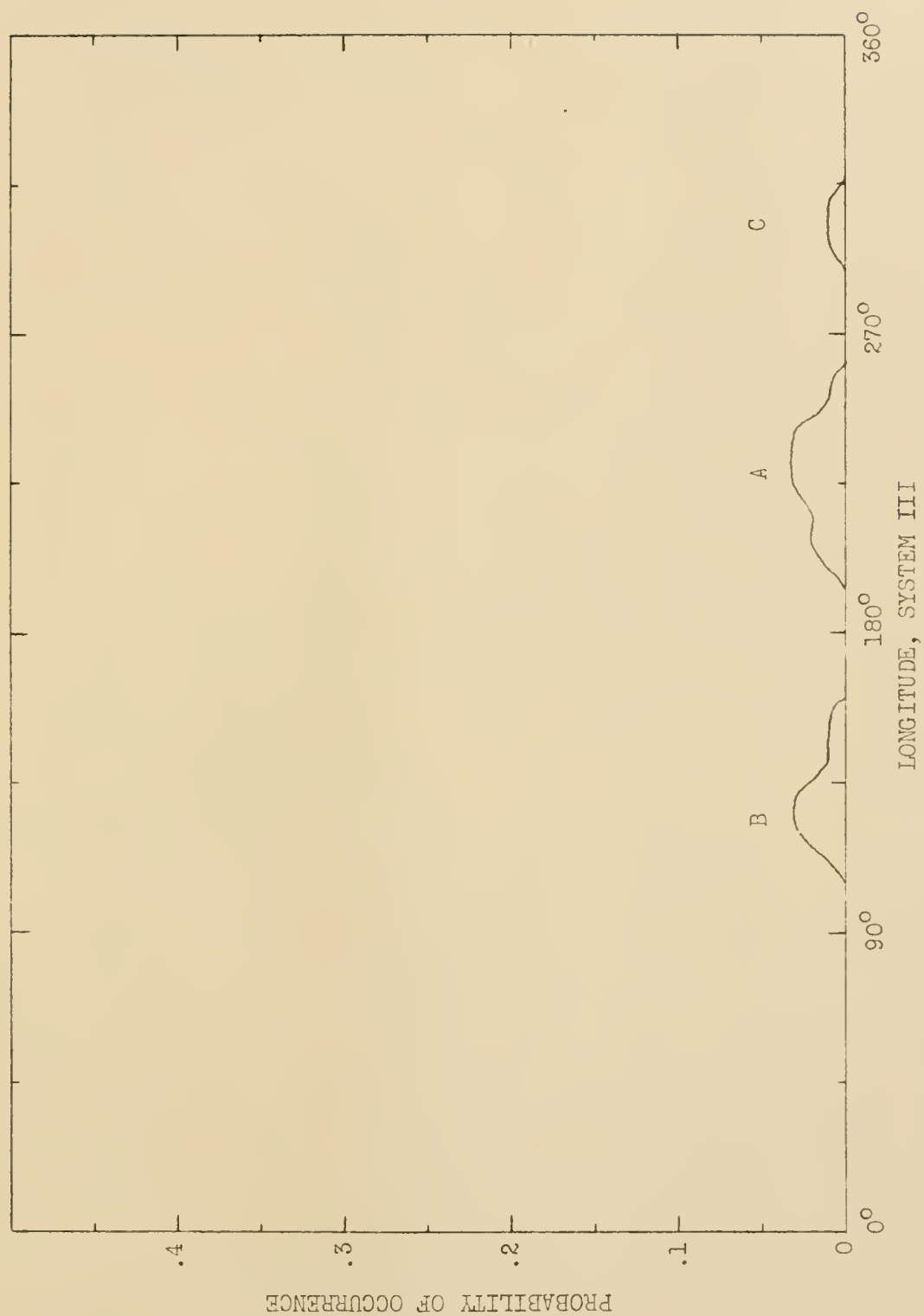


Figure 26.--27.6 Mc/s histogram of Florida and Chile data 1958-1961.

The 1961 smoothed, merged histograms were analyzed in the same manner as Figures 21 through 26, and Table 5 contains the results.

TABLE 5

1961 Data: Location and Width
of the Decameter Sources

Frequency (Mc/s)	Location of the source center (System III)			Width (degrees)		
	A	B	C	A	B	C
10	331	219	82	130	83	68
15	246	143	314	69	70	45
18	239	121	312	62	98	41
20	232	139	306	49	68	31
22.2	227	128	304	42	88	56
27.6	224	120	303	56	26	46

Since our data covering the years 1957 to 1960 have not before been analyzed using the corrected System III rotation period, Table 6 contains the location and width of principal source A for these years. The other sources were not sufficiently defined during the years of maximum sunspot activity.

The shift of source A towards higher longitudes which was evident on the 18, 20, and 22.2 Mc/s histograms of 1961 is probably not a real effect amenable to explanation in terms of a physical event happening at Jupiter. It is the conclusion of the writer that this shift is due to statistical fluctuation in the data. Assuming a random distribution of the System III longitudes of source A at 18 Mc/s for the four apparitions preceding 1961, the longitude of source A at

18 Mc/s on the 1961 histogram is well within 2σ of the mean, where σ is the standard deviation of the sample. The deviation in the longitude of source A on the 1961 18 Mc/s histogram is not statistically significant.

TABLE 6
Location and Width of Source A:
1957 - 1960 Data

Frequency (Mc/s)	1960 Location Width		1959 Location Width		1958 Location Width		1957 Location Width	
10	316	124	---	---	---	---	---	---
16.7*	231	55	---	---	---	---	---	---
18	232	64	214	53	234	34	217	42
20	219	38	---	---	---	---	---	---
22.2	219	32	222	33	219	28	---	---
27.6	222	20	209	13	---	---	---	---

*This histogram is not included in the text.

We noticed earlier in the text that there was a shift of source A towards lower longitudes as we inspected histograms of higher and higher frequency. Evidence of this trend is found by inspection of Figures 1 and 2. It is assumed that the same drift is occurring for B and C, but, since these sources are not as well defined, the shift is not so obvious. The values in Table 4 indicate the longitude displacement with frequency, and Figure 27 is a plot of these values showing the location of the sources as a function of frequency. The combined Florida and Chile data of 1957 - 1961 were used to generate these curves.

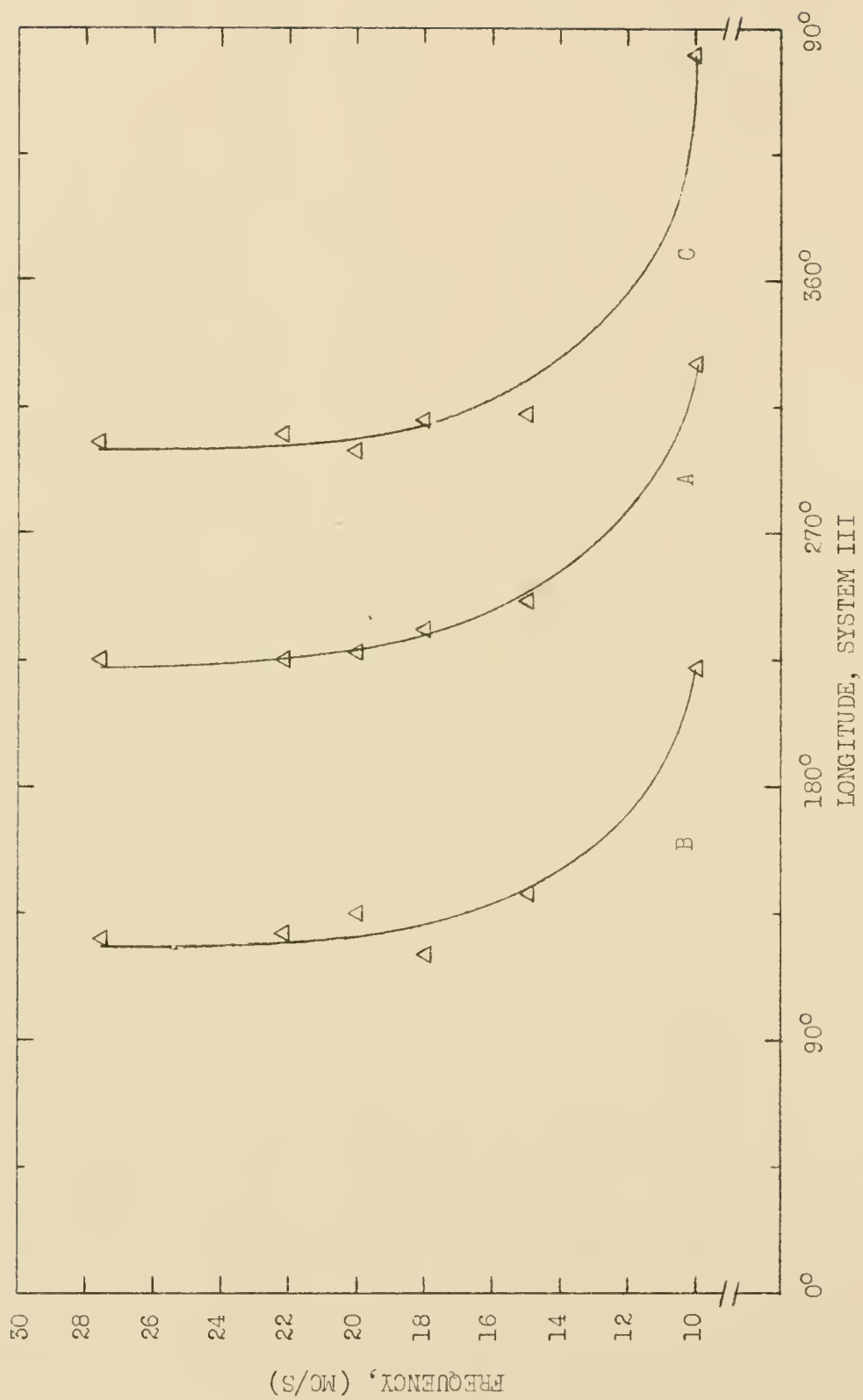


Figure 27.--Location of the decameter sources as a function of frequency.

The longitude shift was first noticed by Gardner and Shain (26), and was pointed out again in 1960 data published by the Florida group (2). It is the conclusion of the writer that this effect is real. What could cause such a shift with frequency? One possible explanation involving the mechanism of the decameter radiation requires radial movement of the source away from the surface of the planet. If, for example, the source is a plasma cloud which has its genesis near the surface of Jupiter and then drifts to higher altitudes, it will necessarily fall behind the rotating surface in order to conserve angular momentum. If, as it rises, it emits radiation of lower and lower frequency, characteristic of cyclotron emission in a magnetic field which is becoming weaker with increasing distance from the surface, then the lower frequencies will come from regions whose sub-Jovian longitudes are greater. The high-frequency decameter radiation, occurring nearer the planet, will be associated with smaller values of longitude. This hypothesis has additional advantages in connection with the directional characteristics of the sources, as we shall see later. One of the difficult points in the argument is accounting for the production of such a source near the surface.

If such a model is a description of the mechanism responsible for the decameter emission, then a calculation of the radial gradient of Jupiter's magnetic field should be possible. An outline of such a calculation, attempted by the writer, follows. If it is assumed that a plasma cloud is ejected radially from the Jovian surface at latitude θ , and that the only force acting on the cloud after ejection is

the force of gravity, then the equations of motion of the cloud relative to axes rotating with the planet are

$$x = v_{y_0} \omega t^2 \cos \theta - \frac{g\omega}{3} t^3 \cos \theta \quad [6]$$

$$y = v_{y_0} t - \frac{1}{2} g t^2. \quad [7]$$

Figure 28 shows the orientation of the coordinate axes.

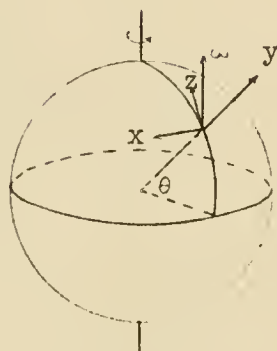


Figure 28.--Coordinate system attached to the Jovian surface.

x is the westerly displacement of the plasma; y is its altitude above Jupiter's surface; v_{y_0} is the velocity of ejection; ω is the angular velocity of Jupiter; t is the time elapsed since ejection; θ is the Jovian latitude; and g is the acceleration due to Jupiter's gravity. If a latitude is chosen, then we are left with four unknowns: x , y , v_{y_0} , and t . Next it is necessary to introduce empirical information in order to reduce the number of unknown quantities. From Figure 27

we can obtain the change in the longitude of the decameter sources with a change in frequency: $\frac{\Delta\lambda}{\Delta f}$.

$$\text{Since} \quad x \cong r\Delta\lambda, \quad [8]$$

$$\text{and} \quad r = r_0 + y, \quad [9]$$

where r_0 is the radius of Jupiter, we arrive at

$$x \cong (r_0 + y) \Delta\lambda. \quad [10]$$

If we know y , we can find x . The number of unknowns has been reduced to three. Spectral data tell us that the frequency drift rates of the Jovian noise bursts range from .01 to 2 Mc/s per minute (12). If we assume that the 27.6 radiation is emitted near the surface at approximately $t = 0$, then it is possible to find the time at which other frequencies will be emitted by choosing a drift rate in the observed range. Now we are left with two unknown quantities y and v_{y_0} . Equations [6] and [7] can be solved simultaneously for the velocity of ejection of the plasma and the altitude of emission of the lower frequency. If it is assumed that the radiation is emitted at the cyclotron frequency, then the magnetic induction can be found at the altitude of emission using

$$f = 2.8 B \quad [11]$$

where f is in Mc/s and B is in gauss. Carrying out the above procedure to find the altitude of emission of several frequencies, one derives the change in B with altitude or the radial gradient of B .

Although the method seems plausible, trouble was encountered due to the large range of observed frequency drift rates. Different values of drift rate gave positive, negative, and infinite velocities of ejection. The drift rates which yielded positive ejection velocities also led to altitudes of emission of the 10 Mc/s radiation below the altitudes where the 18 Mc/s emission occurred. Assuming emission at the cyclotron frequency, this leads one to believe that the Jovian magnetic field strength increases with altitude--an oddity to be sure.

Since the empirical frequency drift rates do not give reasonable velocities of ejection, it is concluded that the equations of motion must be in error. It would seem worthwhile to repeat the calculations including in the equations of motion the effects of electromagnetic forces on the plasma. Such calculations are not within the scope of the present endeavor.

If the sources are connected to the solid disk of Jupiter through its magnetic field, then the separation of the peaks on the histograms should give us a clue to the geometry of this field. By taking the differences between the longitudes locating sources B and C in Table 4, it is found that, excluding the 10 Mc/s values, these sources are separated by approximately 180° . The average separation is 176° , and the greatest deviation from a 180° displacement is only 16° . Considering the arbitrariness involved in determining the center of the sources, these values are quite close together. The next question is: What feature appears on the histograms at the longitude 180° from source A? The answer is--nothing. On all but one of the histograms

in Figures 1 through 26, the feature opposite source A is a null or minimum value of probability. If the location of the sources is an indication of the magnetic field geometry, it appears that Jupiter has a three-pole field. More reasonable would be the assumption of a dipole field with at least one strong inhomogeneity or perhaps two magnetic dipoles oriented in some strange fashion to give the indicated geometry. If source B is indeed a double source, then the latter suggestion does not appear so unreasonable.

The fact that the widths of the peaks on the histograms are less than 180° implies that the radiation has a directional characteristic. If the sources radiated isotropically, then we would receive the signals for the half-revolution of Jupiter during which the source was on the hemisphere facing the earth. That this is not the case is demonstrated by the values in Tables 4, 5, and 6.

The directional property of the sources was noticed by C. A. Shain (27) in data obtained during August - September 1951. K. L. Franklin and B. F. Burke (25) arrived at the same conclusion by analysis of their 22.2 Mc/s data of 1956, and the same year Gardner and Shain (26) found the effect at 19.7 Mc/s. In 1958, Carr et. al. (28), pointed out that the Florida data supported the previous findings, and it was suggested that the existence of a Jovian ionosphere was plausible.

Tables 4, 5, and 6 show that the width of source A decreases with increasing frequency. This is better illustrated in Figure 29, which contains separate curves for each of the years 1958, 1959, 1960,

and 1961, along with a curve derived from measurements of the combination histograms. Again the widths of the peaks on the histograms were measured at one-half the maximum height. All of the curves in Figure 29 indicate that peak width decreases as the frequency goes up. J. W. Warwick has written that beam width is independent of frequency (29). Our data contradict this.

The decrease in the apparent width of the principal decameter source with increasing frequency cannot be explained in terms of a fixed point source lying under an ionosphere. Let us examine the reasoning behind this statement. If a source of electromagnetic radiation lies below an ionized layer in which the maximum electron density is N , then the lowest frequency capable of penetrating this layer at normal incidence is given by the expression

$$f_0^2 = \frac{Ne^2}{\pi m} . \quad [12]$$

f_0 is the critical or plasma frequency for a layer with N electrons/cm.³, e is the electronic charge in electrostatic units, and m is the mass of the electron in grams. All radiation of frequency less than f_0 which is incident on the layer will be reflected. Now suppose that the radiation is not normally incident, but makes an angle i with the normal to the layer. The lowest frequency f that will penetrate the layer at this angle of incidence is related to f_0 by

$$f = f_0 \sec i. \quad [13]$$

All frequencies less than $f_0 \sec i$ are now reflected. If the decameter

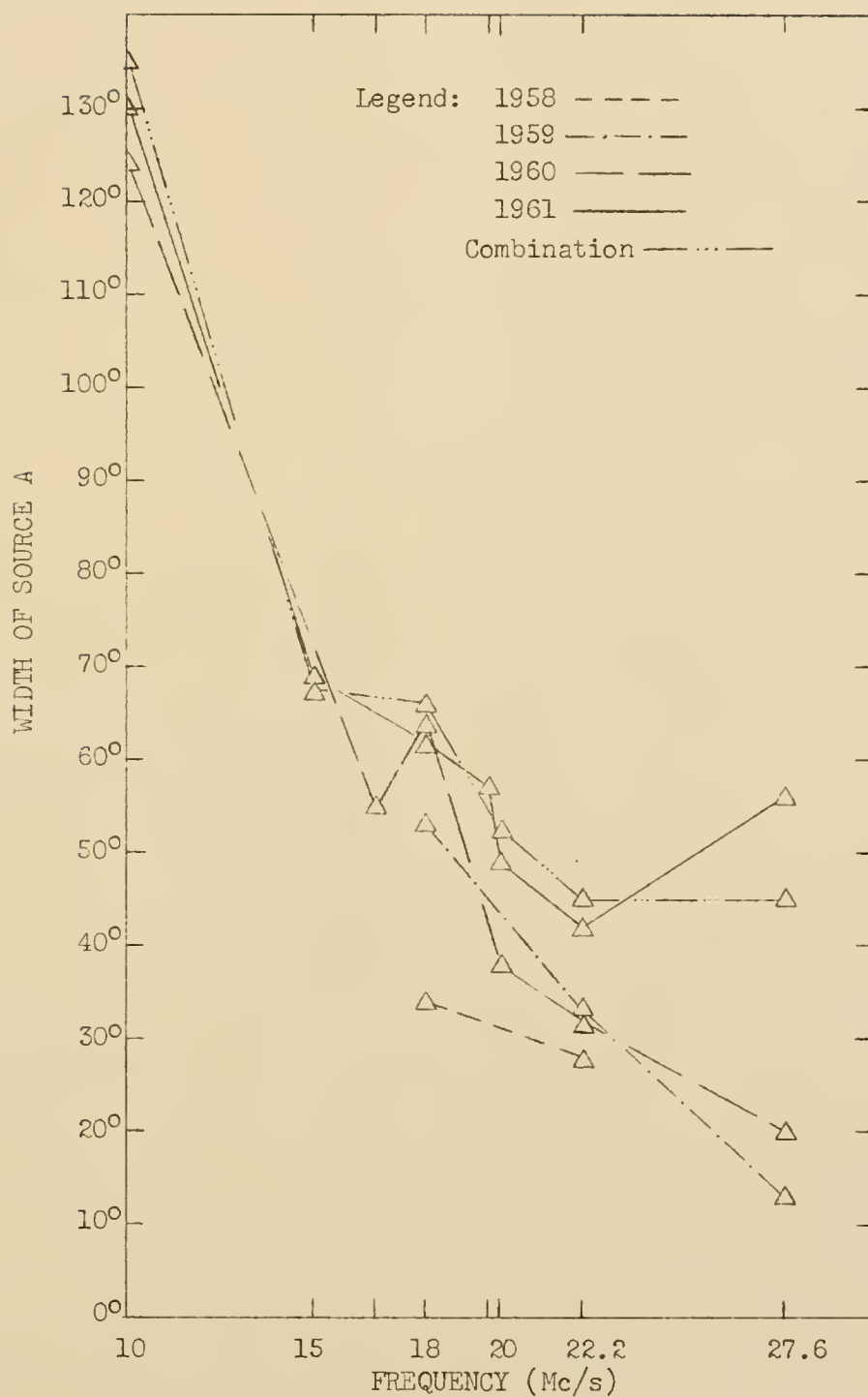


Figure 29.--Variation of source width with frequency.

radiation from Jupiter came from a point source located under an ionized layer whose critical frequency f_o was less than 10 Mc/s, then 10 Mc/s radiation would have a cone of escape with half angle i smaller than that for the cone of escape of 20 Mc/s radiation. As these cones of radiation swept past the earth, the source of the 20 Mc/s radiation would appear broader than the 10 Mc/s. This is not what we observe. The peaks on the histograms become narrower at high frequencies. In the previous discussion, we have neglected the probable presence of a magnetic field on Jupiter. To be exact, we should consider the propagation of electromagnetic waves in a magneto-ionic medium. Such a medium is doubly refracting and two modes of propagation must be considered. A concise explanation is found in reference (30).

How, then, can we explain the two observations: histogram peak widths less than 180° implying directional sources, and the decrease in peak width with increasing frequency? There are two possible explanations, both doing away with the idea of a fixed point source from which all the decameter radiation spews forth.

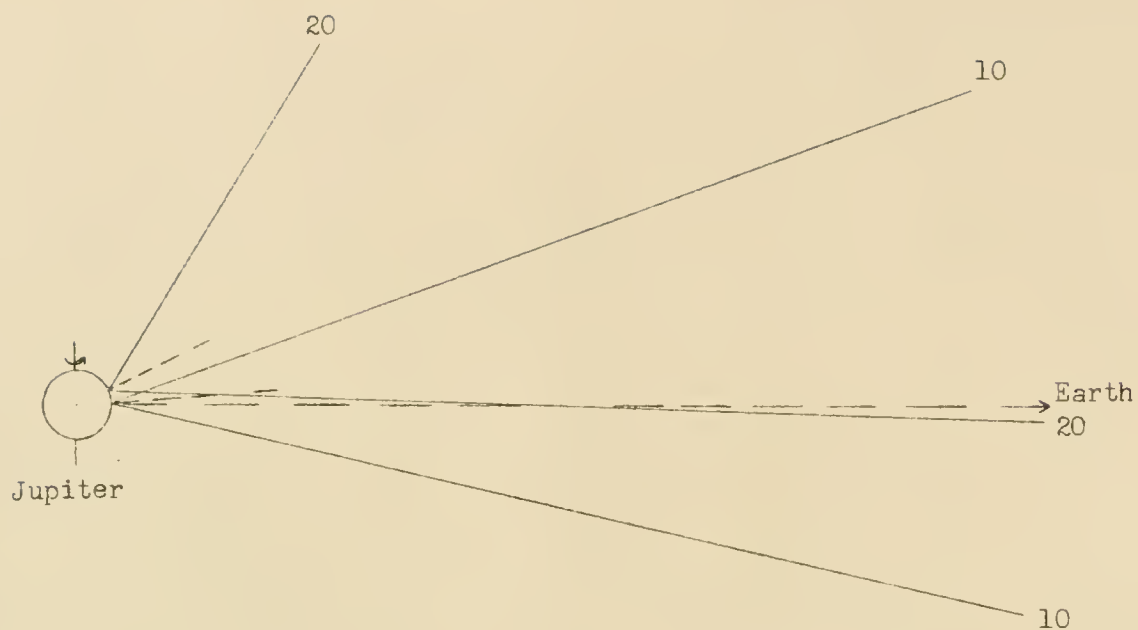
If the high-frequency radiation came from well beneath the layer of maximum ionization in a Jovian ionosphere and the lower frequencies originated further out from the surface of the planet, then the high frequencies would be limited to narrower cones of escape, explaining the peak width variation on the histograms. The idea of radial movement of the source was mentioned previously in connection with the apparent shift of the sources to lower longitudes on the higher frequency curves.

Another possible explanation is that the higher frequencies come from greater latitudes on the planet. The emission cones for the high and low frequencies could intersect so that as the sources rotate around the planet, an observer on earth would be exposed to a wider segment of the low frequency beam. Figure 30a shows the geometry of radio reception at the earth. The half angle of the emission cones for different frequencies is determined by the electron density in the Jovian ionosphere. Figure 30b shows the regions of radiation that would pass over the earth as Jupiter rotates. Segment BC corresponds to 20 Mc/s reception and AD corresponds to 10 Mc/s reception. Notice that the 10 Mc/s cone has been displaced in the direction of greater System III longitude to conform with the data.

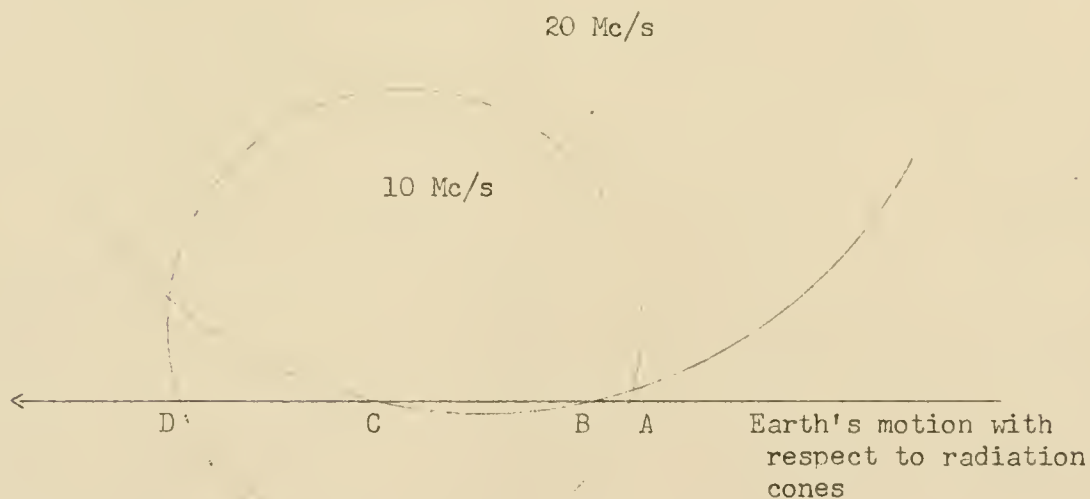
Both of the above explanations retain the idea of a Jovian ionosphere and separate the points of origin of the different decameter wavelengths. Further evidence in favor of a Jovian ionosphere will be brought up in Chapter 3 in connection with the long-term inverse correlation with the sunspot cycle.

Intensity Histograms

So far, the conclusions regarding source structure have been based on the probability histograms of Figures 1 through 26. A natural question to ask is, "How does the intensity of the decameter radiation vary with Jovian longitude?" In order to answer this question, intensity histograms have been constructed and are presented in Figures 31 and 32. A few words of explanation about the method used in developing these histograms seem appropriate. In reducing the slow



a



b

Figure 30.--Geometry of radio reception of Jovian outbursts assuming a Jovian ionosphere and latitude separation of the frequencies emitted from a single source.

speed pen recordings of Jupiter noise, the average height above the galactic level of the three highest pulses in a storm is determined, and the ratio of this average height to the level of galactic noise at the position of Jupiter is found. This ratio is a measure of the relative intensity of the Jovian noise storm. To make a histogram table, it is also necessary to know what longitudes (System III) were on Jupiter's central meridian while the storm was in progress. Knowing these things, we can construct a histogram table by recording the relative intensity value in each column representing longitudes that the storm covered. Having done this for a particular frequency and apparition, we add up the values in each column and divide by the number of entries to obtain an average intensity for each 5° increment of Jovian longitude. These values are then smoothed by three-point averaging and plotted. Of course, a better method would have been to measure the intensity of the storm every 8.3 minutes, corresponding to 5° rotation of the planet; however, the amount of time required would have been considerable. A certain amount of smearing results from using the average-three-high-peak ratio as a measure of the intensity of the whole storm. Very often the three high peaks are clustered close together while the complete storm might last as long as two hours, corresponding to more than 70° of rotation.

Figure 31 contains 18 Mc/s intensity histograms for the five years, 1957 through 1961. The only prominent feature common to all the curves is the general dip in the average intensity centered at about 40° . This lines up quite well with the null in the probability histograms.

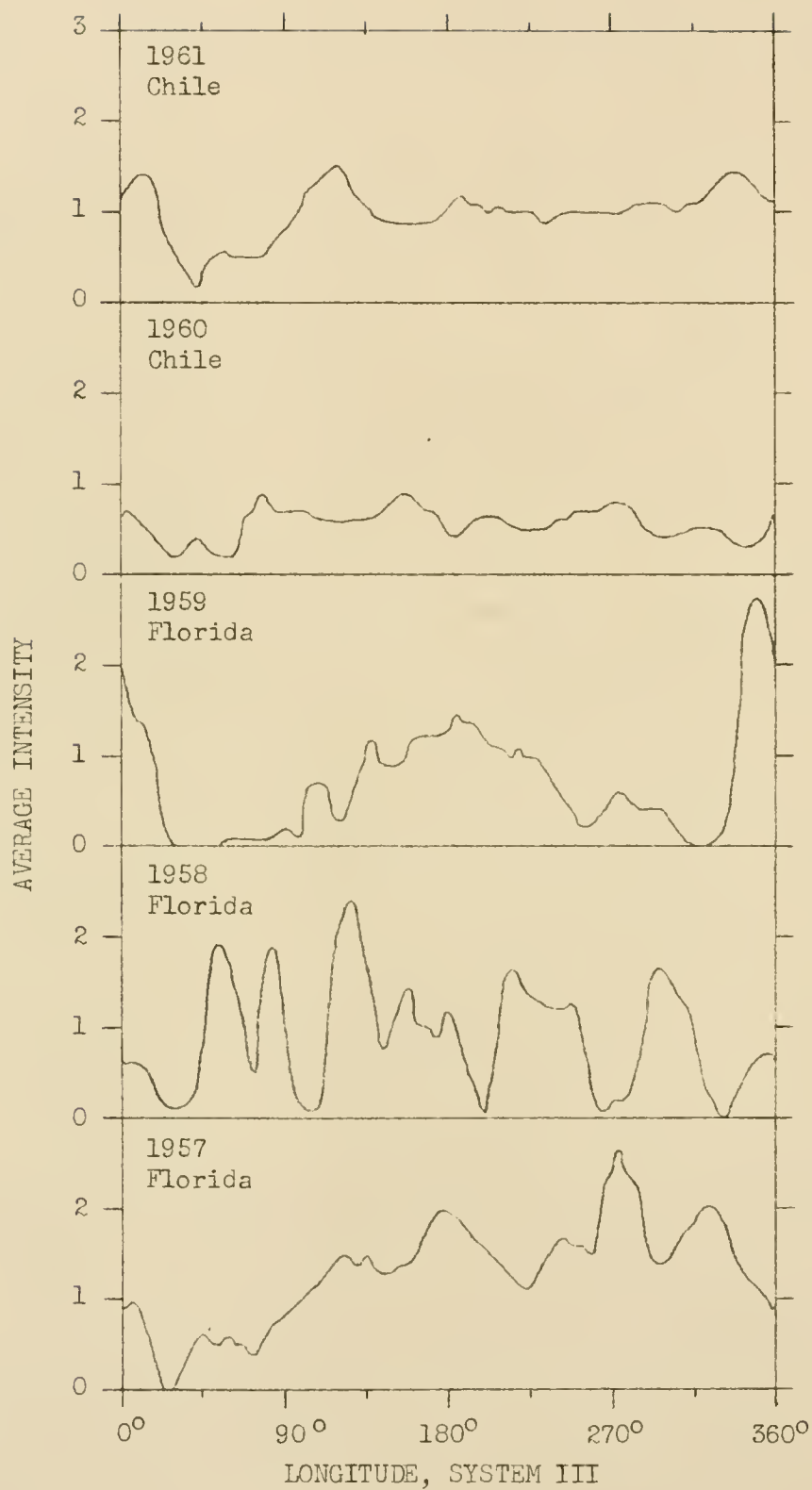


Figure 31.--18 Mc/s intensity histograms.

The following points are of interest. The peak at 120° on the 1961 curve corresponds to the location of source B. On the 1960 curve there is a small peak at 40° in the center of the general null extending from 20° to 60° . The 1959 curve shows two dips, one at 40° and another at 320° . There are also two peaks, a broad one centered at 180° and a narrow one at 355° . The probability histogram of 1959 shows source A at 214° . The 1958 plot is quite jagged and the null at 40° is not conspicuous to say the least. The broad peak extending from 200° to 260° corresponds to the position of source A. The dip on the 1957 plot occurs at 25° , and none of the other features line up with sources on the probability histogram for that year. There does not appear to be any regular pattern in the intensity behavior from year to year.

Figure 32 contains four more 1961 intensity histograms. The upper two curves are for 10 Mc/s in Chile and Australia. It appears from the flatness of these histograms that there is almost no intensity variation with longitude at 10 Mc/s. The 19.7 Mc/s curve of the Australia data shows the prominent dip at about 40° . Notice that the ordinate scale is compressed. The 27.6 Mc/s intensity histogram is the only one that looks like its corresponding probability histogram. The three peaks lie at 218° , 116° , and 295° , and they match the longitudes of sources A, B, and C respectively. This is probably due to the fact that there was such a small amount of 27.6 Mc/s radiation received from Jupiter. What was received came only when the sources were near the central meridian.

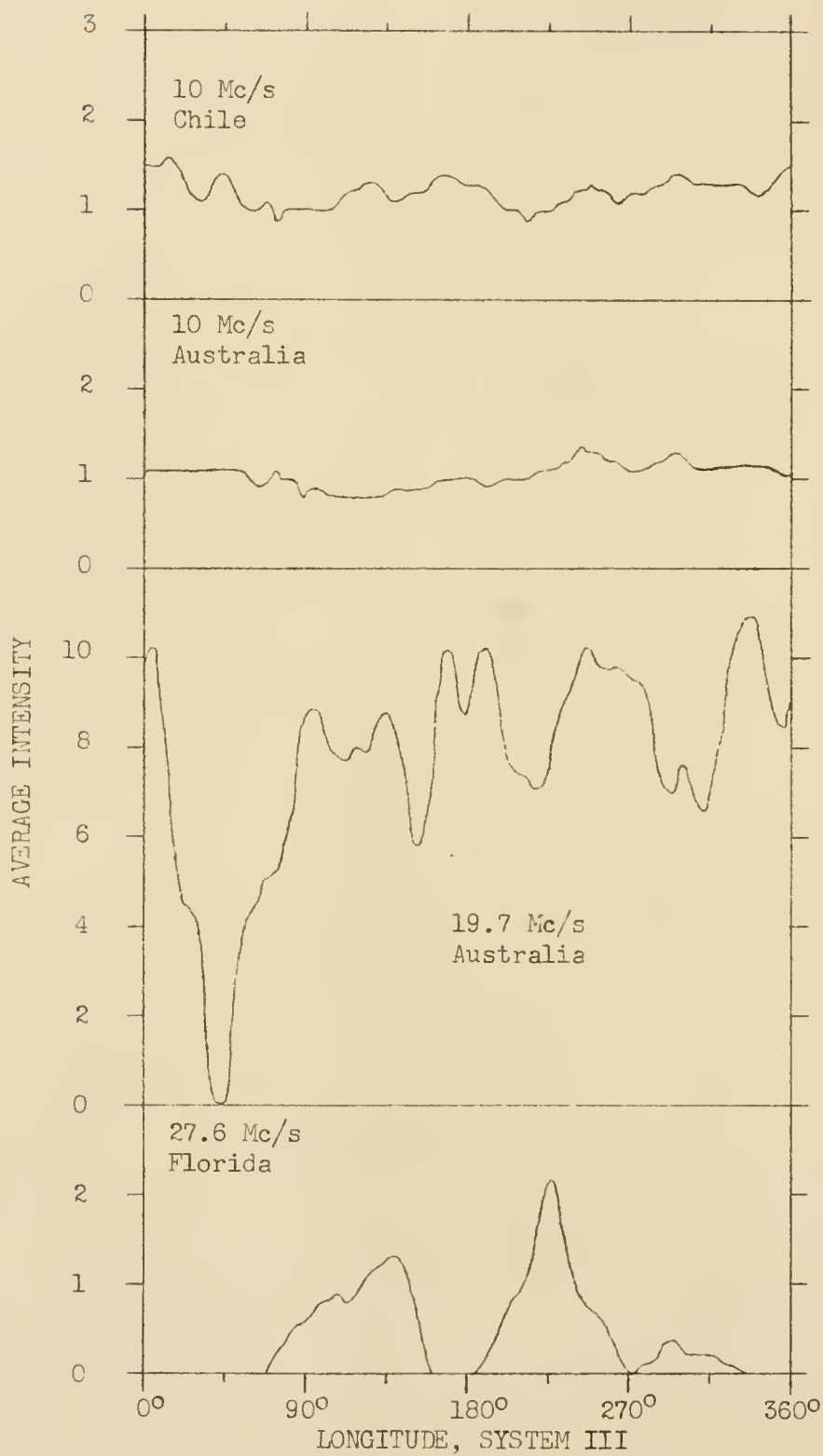


Figure 32.--1961 intensity histograms.

Except for the general null at about 40° corresponding to the longitude from which we very seldom get radiation, there is little correlation between the intensity histograms and the probability histograms. The flat appearance at 10 Mc/s and the random nature of the other plots, where there is enough data to give a fair representation, lead to the conclusion that the most intense radiation does not necessarily come from those longitudes which are the most frequent sources of radiation. In other words, there does not appear to be any well-defined variation of intensity with longitude. Certainly, there is room for more investigation along these lines.

As mentioned earlier, a truer picture of the intensity variation would have been obtained by breaking up the periods of activity into shorter segments, say 10-minute intervals, and taking measurements of the maximum pulse height in each. This was done for the 1961 Chile data at 18 Mc/s. The measurements and theory involved are described below.

Let D = deflection due to Jupiter plus the galaxy

G = deflection due to the galaxy alone

P_J = power from Jupiter alone

P_G = power from the galaxy alone.

D and G are measured on the pen recordings. The power ratio is given by the expression

$$\frac{P_J}{P_G} = \frac{D^2 - G^2}{G^2} = \frac{D^2}{G^2} - 1 . \quad [14]$$

The flux density is the power per unit area per cycle per second;

hence, the flux ratio is

$$\frac{F_J}{F_G} = \frac{D^2}{G^2} - 1. \quad [15]$$

Solving for the Jovian flux density we get

$$F_J = F_G \frac{D^2}{G^2} - 1 \quad \text{in watts/m}^2/\text{cps}. \quad [16]$$

The flux density from the galaxy is determined in the following manner.

Let e = charge on the electron (1.6×10^{-19} coulombs)

A = effective area of the antenna

T = transmission coefficient of the transmission
line (percentage of power getting through)

R = output resistance of the calibrator

$\overline{I}_G$ = product of the average calibration current in
amperes giving the same deflection as the
galactic signal and the scale factor 6.5.

$$\text{Then} \quad F_G = \frac{e \overline{I}_G R}{AT}. \quad [17]$$

The Jovian flux density is given by

$$F_J = \frac{e \overline{I}_G R}{AT} \left(\frac{D^2}{G^2} - 1 \right). \quad [18]$$

The constants for the 18 Mc/s Chile data of 1961 are the following:

$$\overline{I}_G = (.014)(6.5) = 0.091 \text{ amp}$$

$$R = 75 \text{ ohms}$$

$$T = 0.7$$

$$A = 0.13 g \lambda^2 = (0.13)(15)(16.7\text{m})^2 = 543\text{m}^2$$

where g is the average power gain of the interferometer antenna, and λ is the wavelength in meters. The average value of the calibration current $\overline{I}_G$ used was that determined for the three-month period June - August, 1961. By multiplying these factors together, we get a value of 2.88×10^{-21} watts/m²/cps for the galactic flux density at 18 Mc/s. Equation [18] now takes the special form

$$F_J = 2.88 \times 10^{-21} \left(\frac{D^2}{G^2} - 1 \right). \quad [19]$$

Since the Jovian flux is proportional to $\left(\frac{D^2}{G^2} - 1 \right)$, and D is a measure of the highest pulse in a ten-minute interval, a plot of

$\left(\frac{D^2}{G^2} - 1 \right)$ versus longitude will reveal the variation of Jovian peak flux density with longitude. As before, a histogram table was compiled, this time using values of $\left(\frac{D^2}{G^2} - 1 \right)$. The average value for each 5° increment of longitude was calculated. The result is the flux density histogram in Figure 33. The most prominent feature is the dip centered at about 60°. The dashed and solid lines at the bottom of the figure designate longitude intervals in which less than 10 or more than 20 Jupiter noise storms occurred respectively. The sections of the curve below which there is no line correspond to longitude segments in

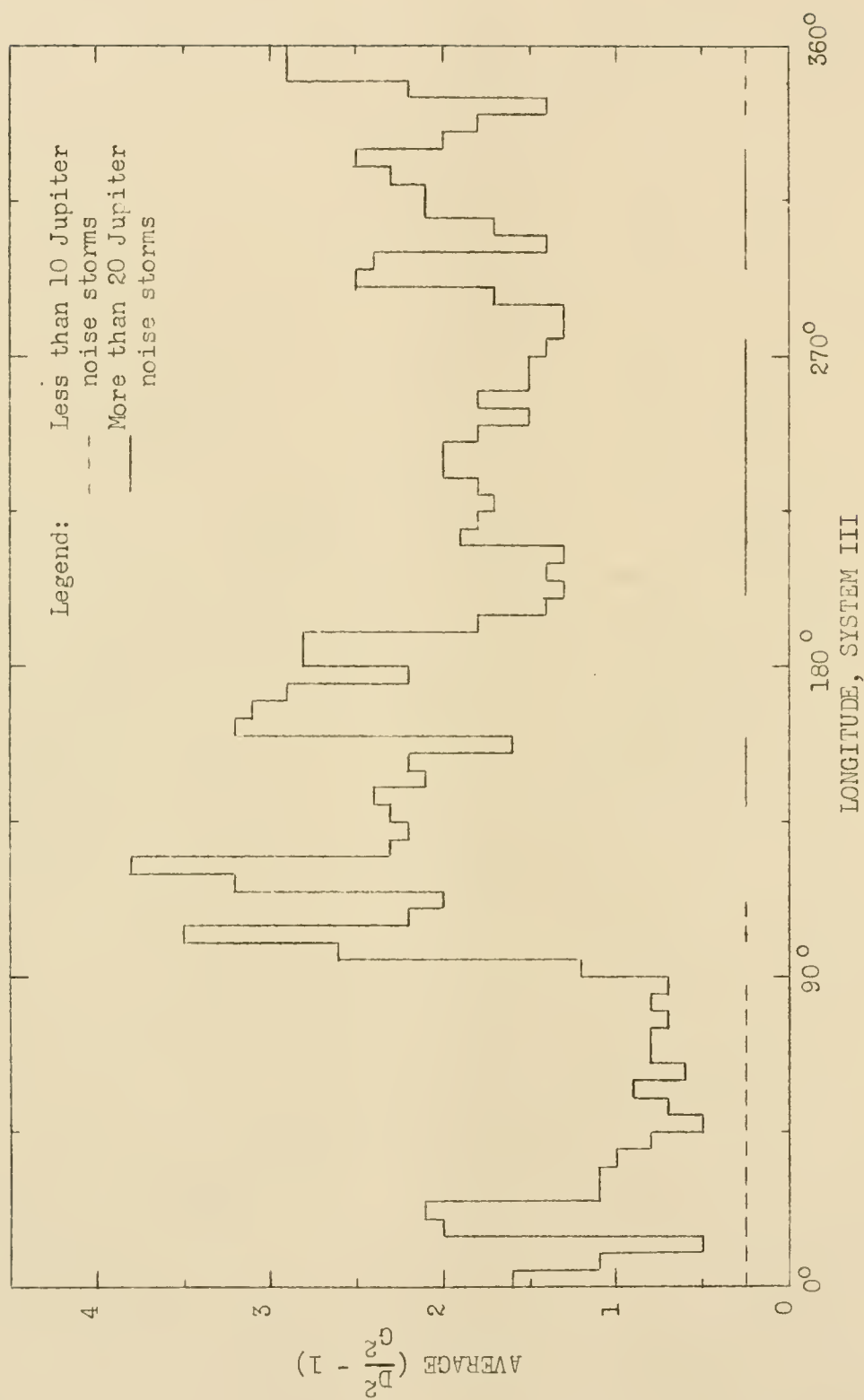


Figure 33.--Jovian flux density histogram calculated using the Chile, 18 Mc/s data of 1961.

which 10 to 20 decameter storms occurred. It is interesting to note that the features which stand out on the histogram (the dip at 60° and the peak at 110°) occur where the statistics are the poorest. Where the statistics are the best, from 125° to 330° , there are no prominent maxima or minima. There is almost no correlation between this curve and the 18 Mc/s Chile probability histogram of 1961. Thus, the flux density histogram supports our previous conclusion that there is no well-defined correlation between the intensity of the decameter radiation and Jovian longitude.

To convert the ordinate scale in Figure 33 to values which correspond to peak Jovian flux densities, multiply by 2.88×10^{-21} watts/m²/cps. If we assume that the average flux is proportional to the peak flux, i.e.,

$$\overline{F_J} = K (F_J)_{\text{max}}, \quad [20]$$

then all we need to know in order to convert the ordinate scale to values which correspond to average Jovian Flux densities is the constant K. G. W. Brown, a member of the radio astronomy group at the University of Florida, has recently determined K to be approximately 0.11. If the ordinate values in Figure 33 are multiplied by the two factors 2.88×10^{-21} and 0.11, then they become average Jovian flux densities in watts/m²/cps.

Activity Studies

1961 Activity Plots

Up to this point we have been examining probability and intensity histograms to obtain information about the longitude distribution of the decameter radiation from Jupiter. These investigations have been referred to as "source studies." Now we wish to take another point of view and find out how the Jovian activity varies from day to day. Such information is important in searching for suspected correlations with other daily indices.

A measure of the Jovian decameter activity on a particular day is the "daily activity index rate." This quantity is computed on the IBM 709 and is explained at the beginning of this chapter. Briefly, it is the sum of the activity indices of all Jovian storms on a given date, divided by the total duration in minutes of the listening period on that date. Remember that the activity index of a Jovian noise storm was defined as the product of the intensity, the duration in minutes, and a normalization factor. The duration of the listening period appears in the denominator of the daily activity index rate calculation in order to remove the effects of variation in the amount of good receiving time from night to night. If a watch period lasted for six hours, one would expect to get more Jovian noise than during a night when listening conditions were such that there was only one hour of good reception.

Figures 34 through 38 contain daily activity plots of the 1961 data. Those frequencies which were covered at two stations

appear in a single figure with data from one station plotted above the other, corresponding dates lying on a vertical line. The starting and ending dates of the watch, as well as periods of no monitoring, are marked on the plots. Dates when listening conditions were poor due to atmospheric or man-made interference are signified by "x." Dates when there was no watch due to equipment failure or absence of the observer are marked "O." The plot of the Florida data in Figure 35 shows the dates of zenocentric inferior conjunction of Mercury, Venus, Earth, and Mars. This will be discussed later in the text. The 15 Mc/s, 18 Mc/s, 22.2 Mc/s, 27.6 Mc/s, and 10 - 20 Mc/s data are found in Figures 34 through 38, respectively. During the 1961 apparition, there were only eight nights when the ionosphere at the Chile station permitted reception at 5 Mc/s. Although a constant vigil was maintained in Florida at 31 Mc/s for a five-month period, only five pulses of possible Jovian origin were received. For these reasons, no activity plots were constructed for 5 Mc/s and 31 Mc/s.

Figure 39 was obtained by combining the two activity plots of Figure 35. This was accomplished by recording the larger of the two values of daily activity index rate for each day. By doing this, we consider only the best Jovian reception and eliminate many of the "no-data-days" when atmospheric conditions blanked out reception on one station or the other. Figure 39 gives the best indication of Jupiter's activity from day to day at 18 Mc/s during the 1961 apparition. A similar combination of data was performed on the activity plots in Figure 36, and the resulting graph is found in Figure 40, which shows Jupiter's 22.2 Mc/s activity during 1961.

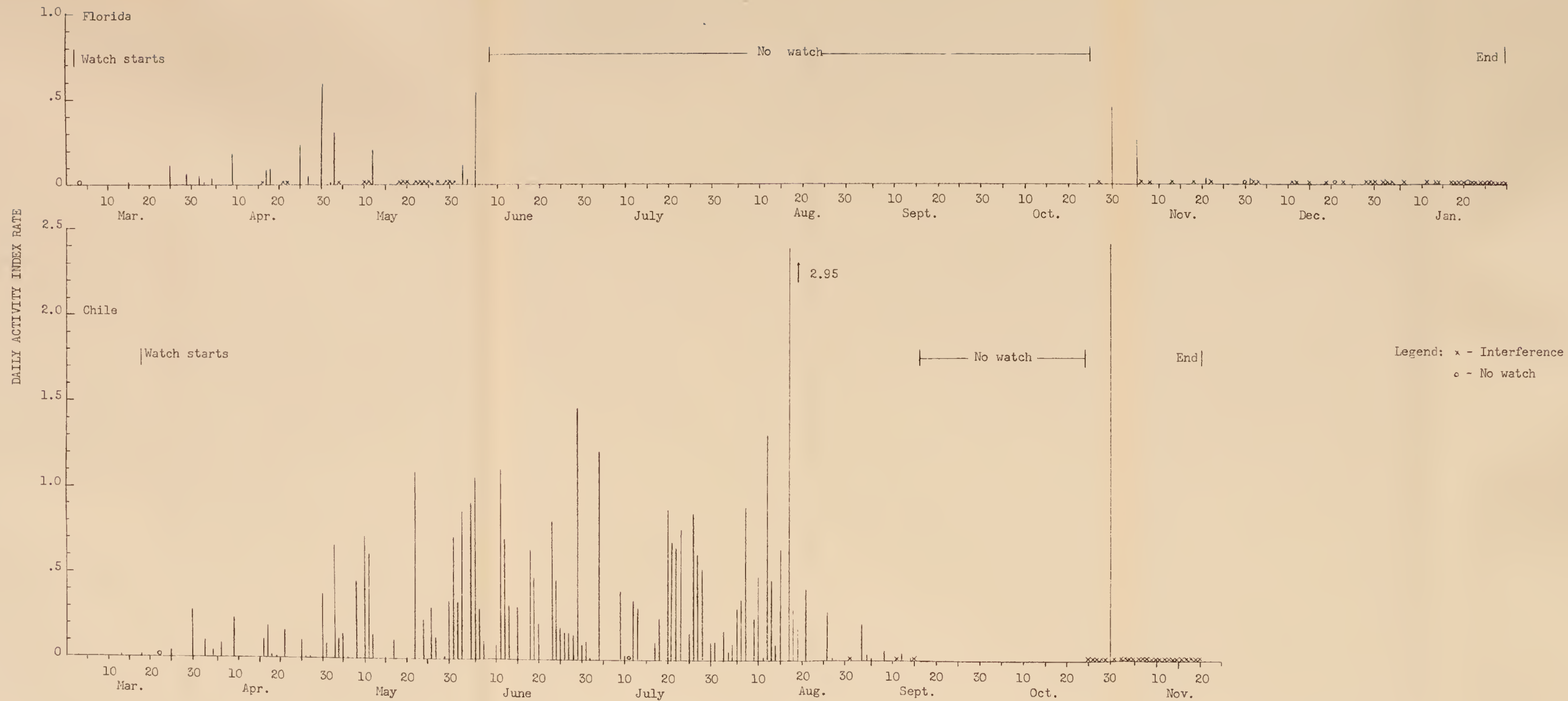


Figure 34.--15 Mc/s activity plots of 1961 data.

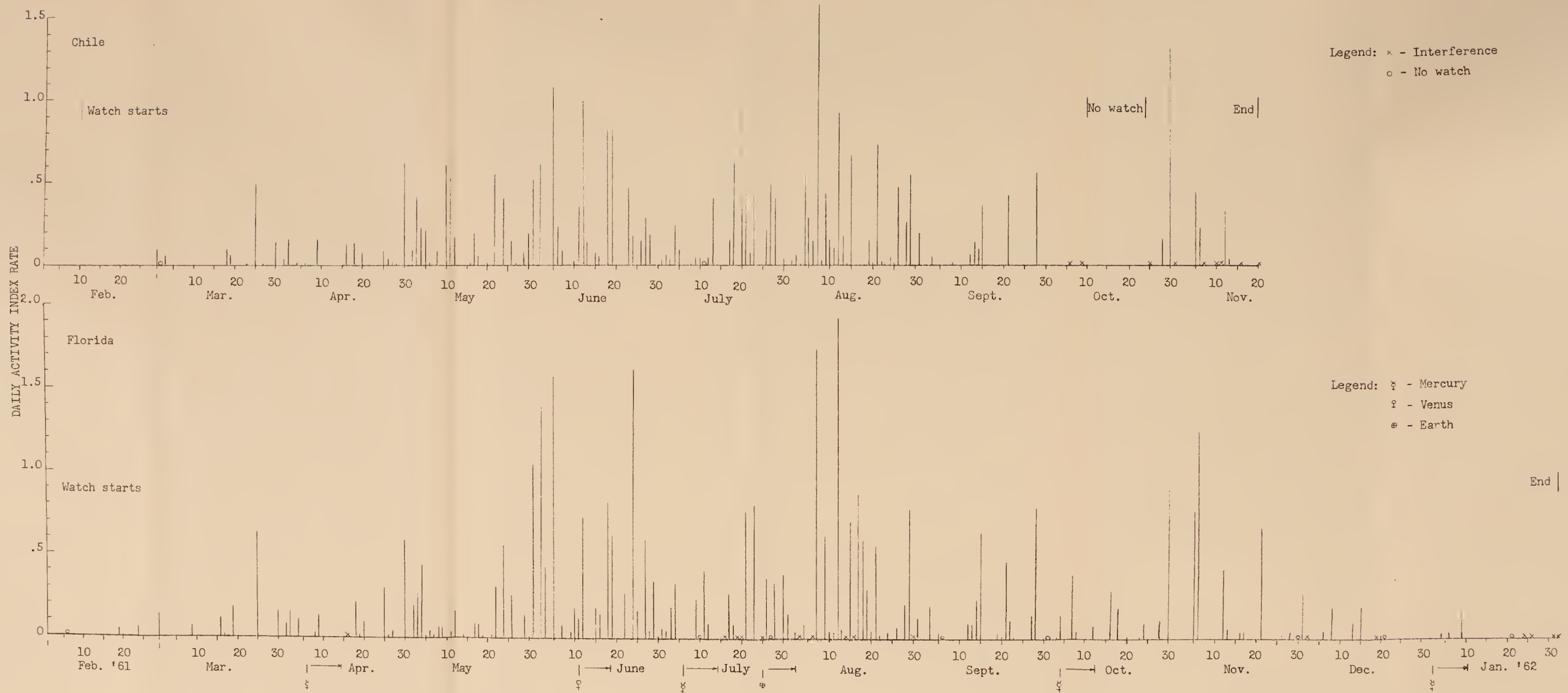
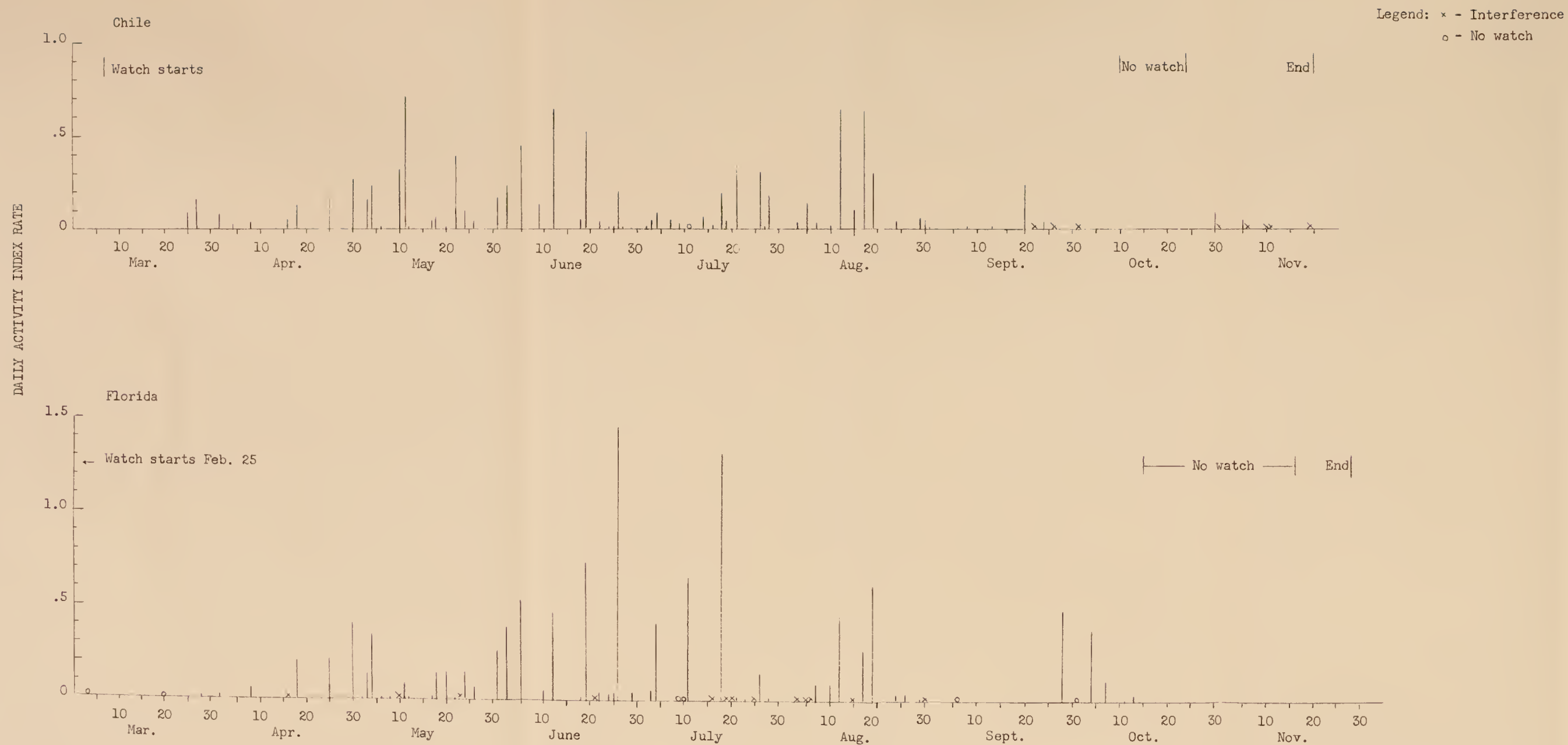


Figure 35.--18 Mc/s activity plots of 1961 data.



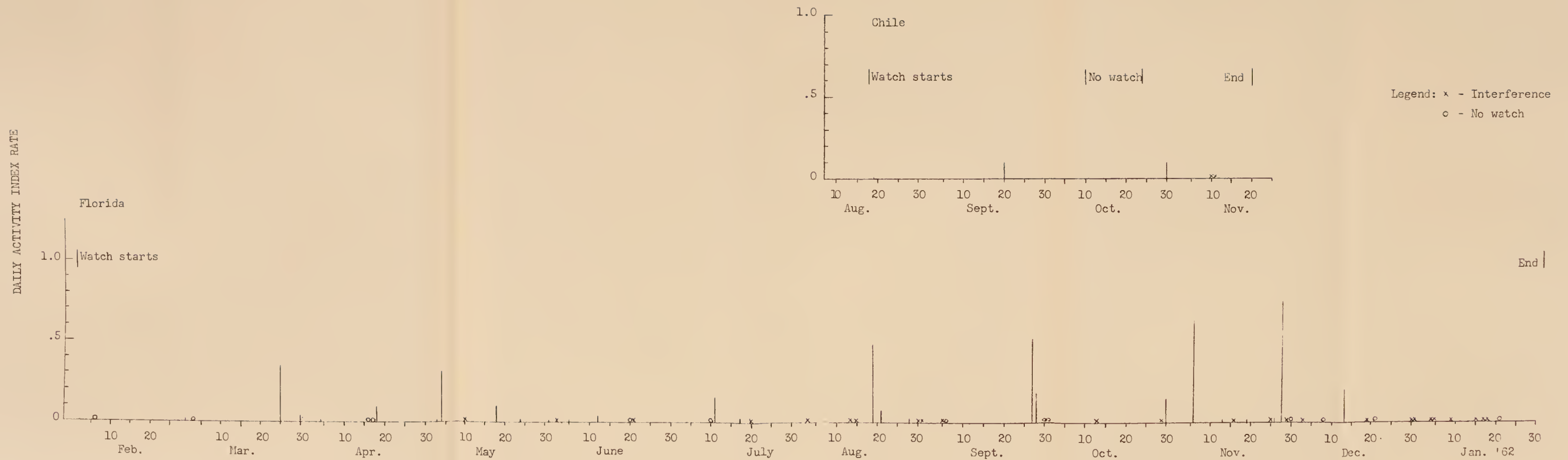


Figure 37.--27.6 Mc/s activity plots of 1961 data.

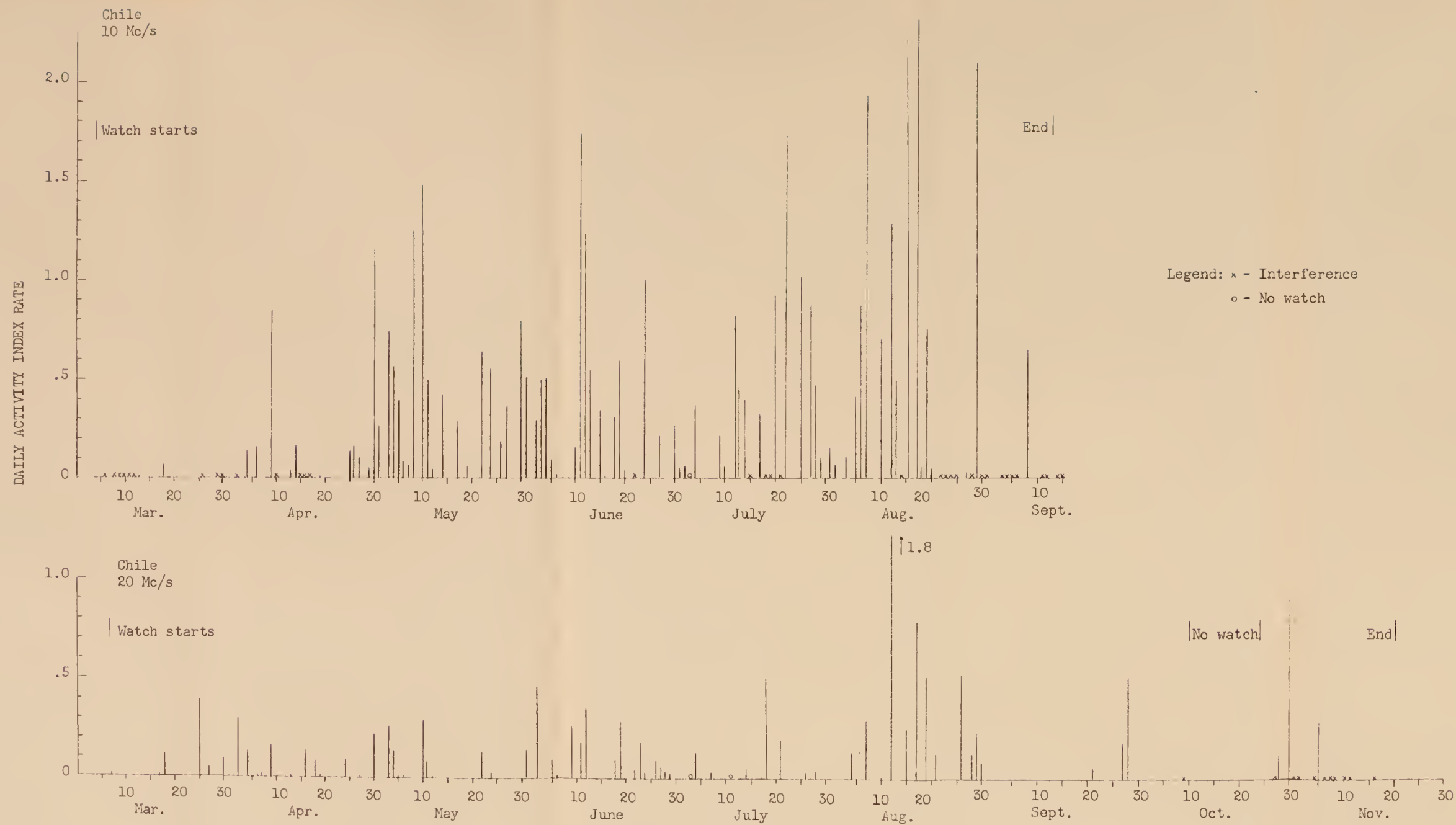


Figure 38.--10 Mc/s and 20 Mc/s activity plots of 1961 data.

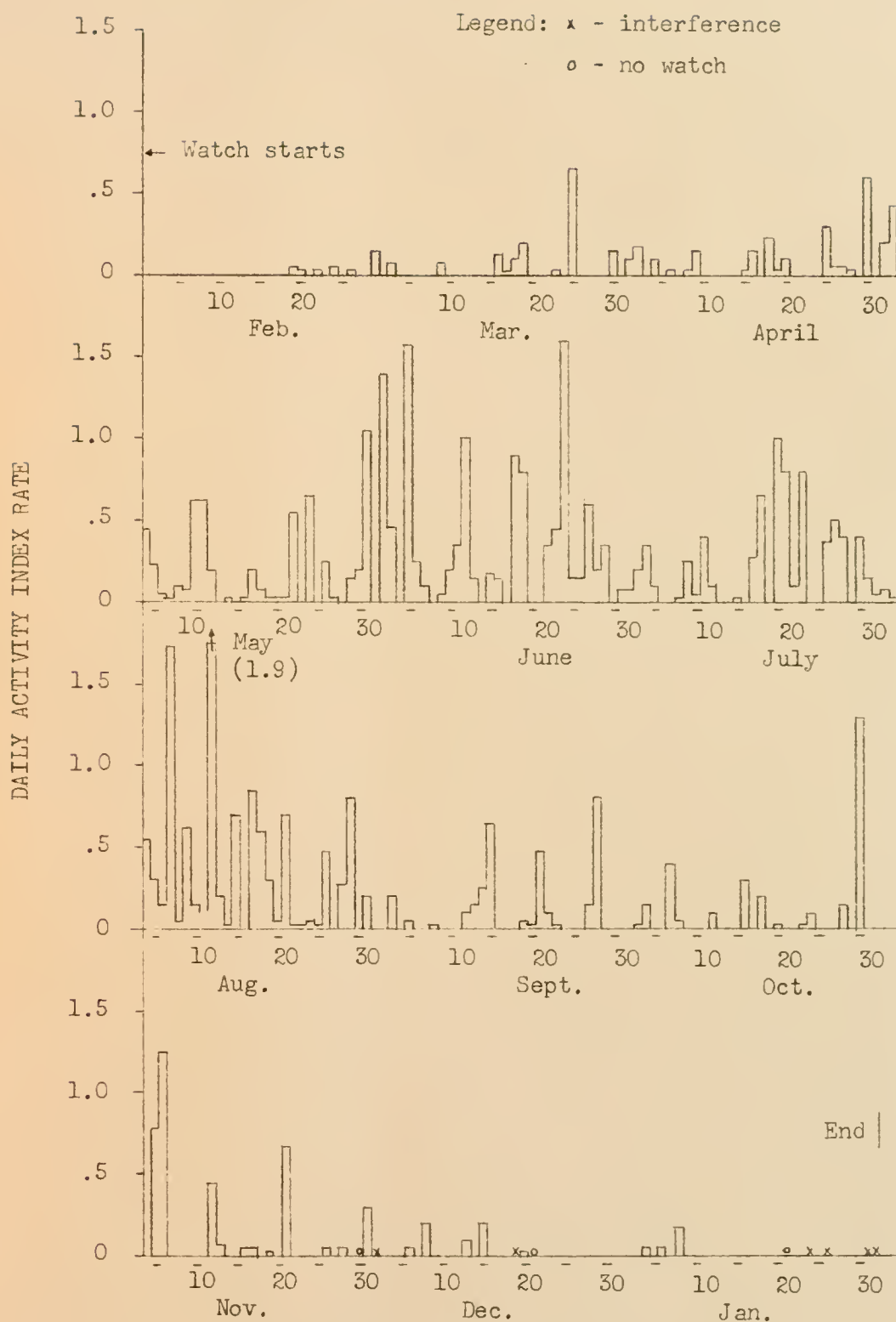


Figure 39.--18 Mc/s activity plot, 1961 data of Florida and Chile combined.

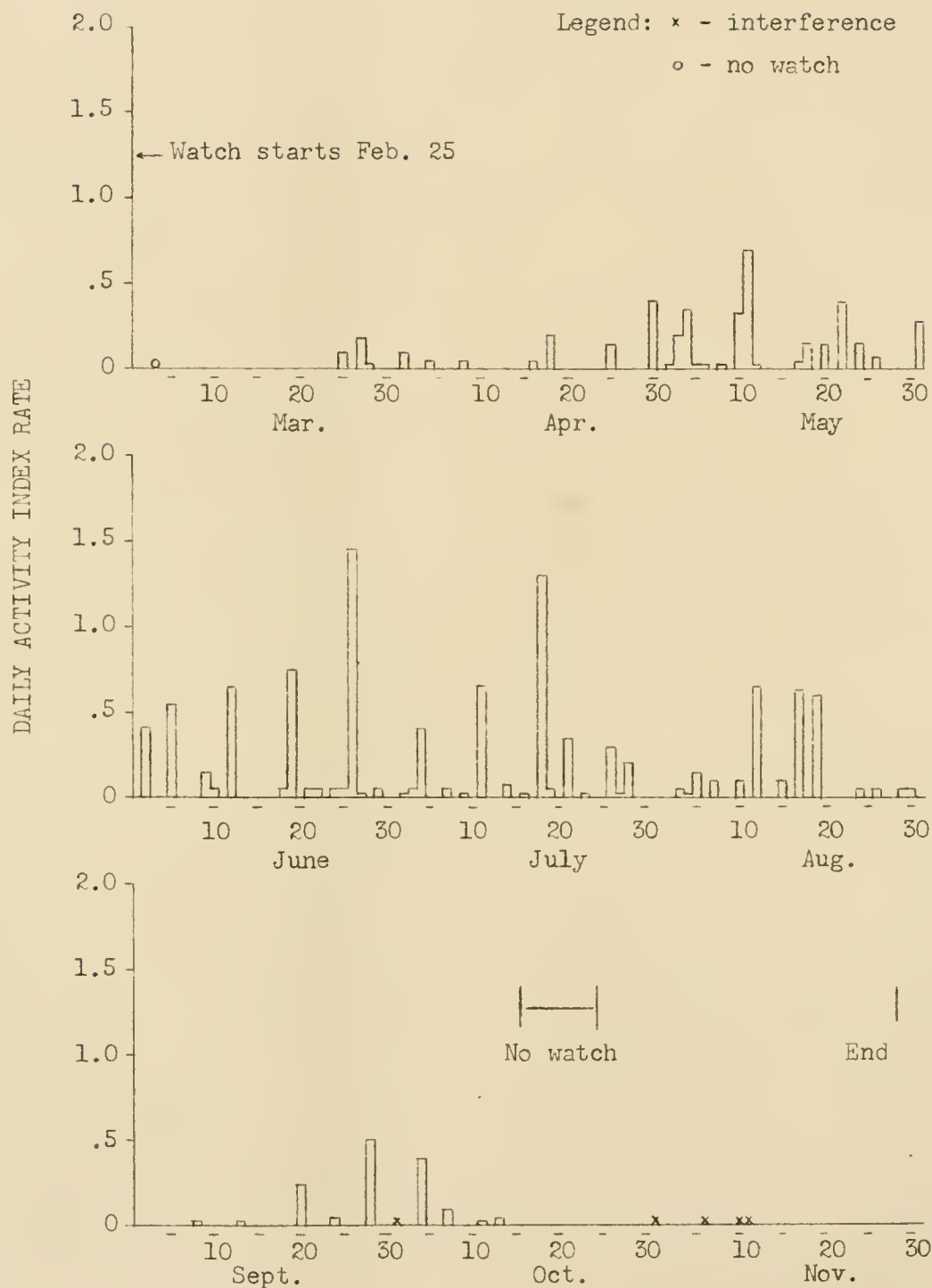


Figure 40.--22.2 Mc/s activity plot, 1961 data of Florida and Chile combined.

Activity Plots for 1957 - 1960

All of the Jupiter data obtained by the Florida group back through 1957 have been analyzed in the same manner as the 1961 data. Daily activity index rate calculations were performed on the IBM 709. Figures 41 - 45 contain the activity plots of the different frequencies monitored in Florida and Chile during the 1960 observing season. Figure 46 contains activity plots of 18 Mc/s, 22.2 Mc/s, and 27.6 Mc/s data collected in 1959. Figure 47 contains the activity plots of the 1957 and 1958 data. It should be pointed out that the daily activity index rate values, which make up the plots in Figures 34 - 47, have not been adjusted to correspond to a standard Earth-Jupiter distance. This would be a worthwhile addition to the computer program.

A natural question is suggested. Do any cycles appear in the day-to-day variation of Jupiter's decameter emissions? In 1957, a quite-evident eight-day cycle was found in the 18 Mc/s data (28). The daily activity plots in Figures 34 through 47 do not exhibit any striking periodicities of this sort; however, a method of "smoothing" applied to the daily activity plots does reveal evidence of a seven- to eight-day recurrence in Jovian activity. This will be discussed later in the chapter.

The Angular Rate Effect

S. E. and K. M. Strom have suggested as a possible mechanism for the Jovian decameter bursts that as Jupiter occults a distant discrete radio source (or "radio star"), it focuses the energy from this source at a point near the earth's orbit (31). Adopting a model Jovian



Figure 41.--Activity plot of Florida 18 Mc/s 1960 data.

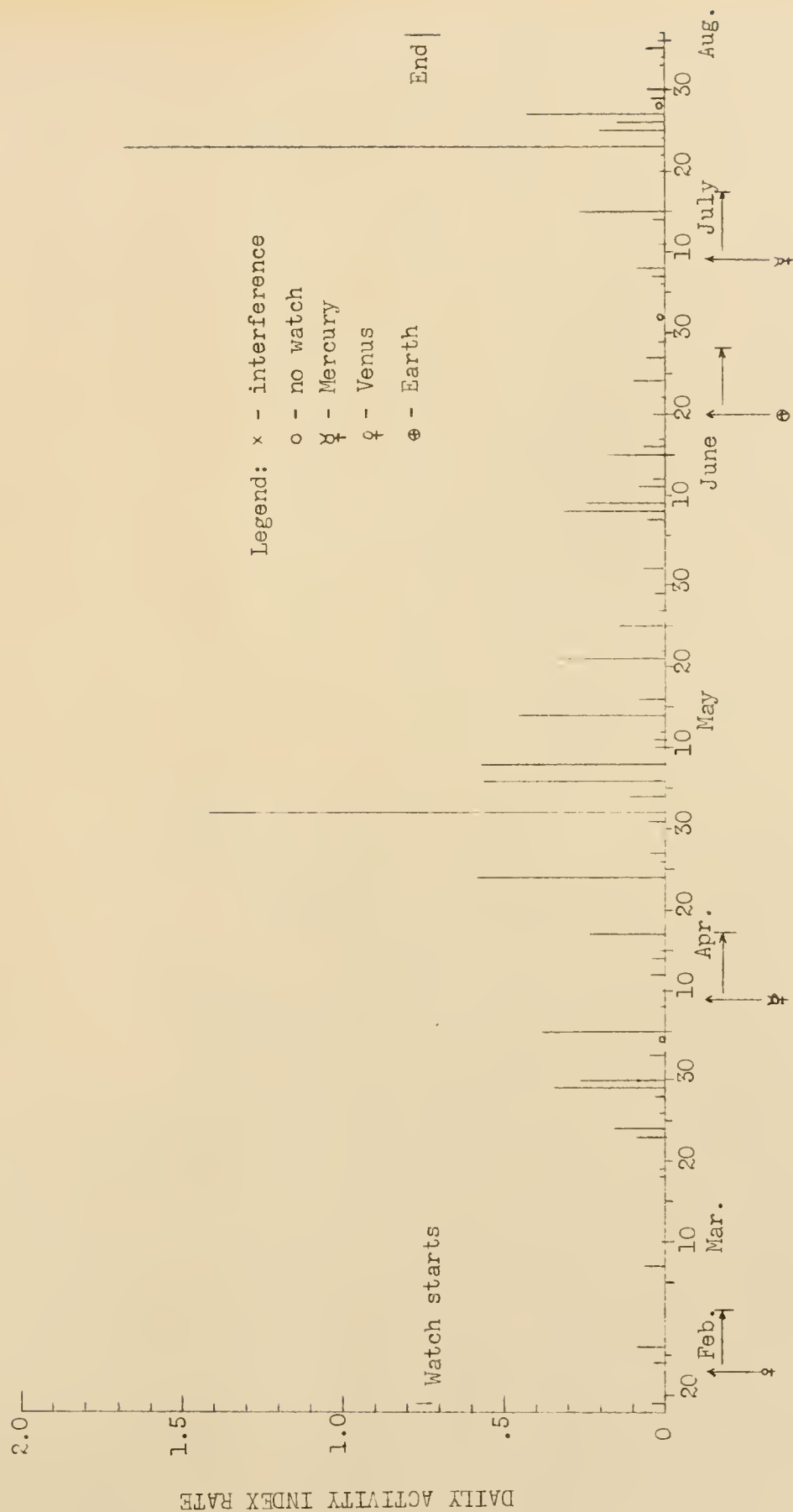


Figure 42.--Activity plot of Chile 18 Mc/s 1960 data.

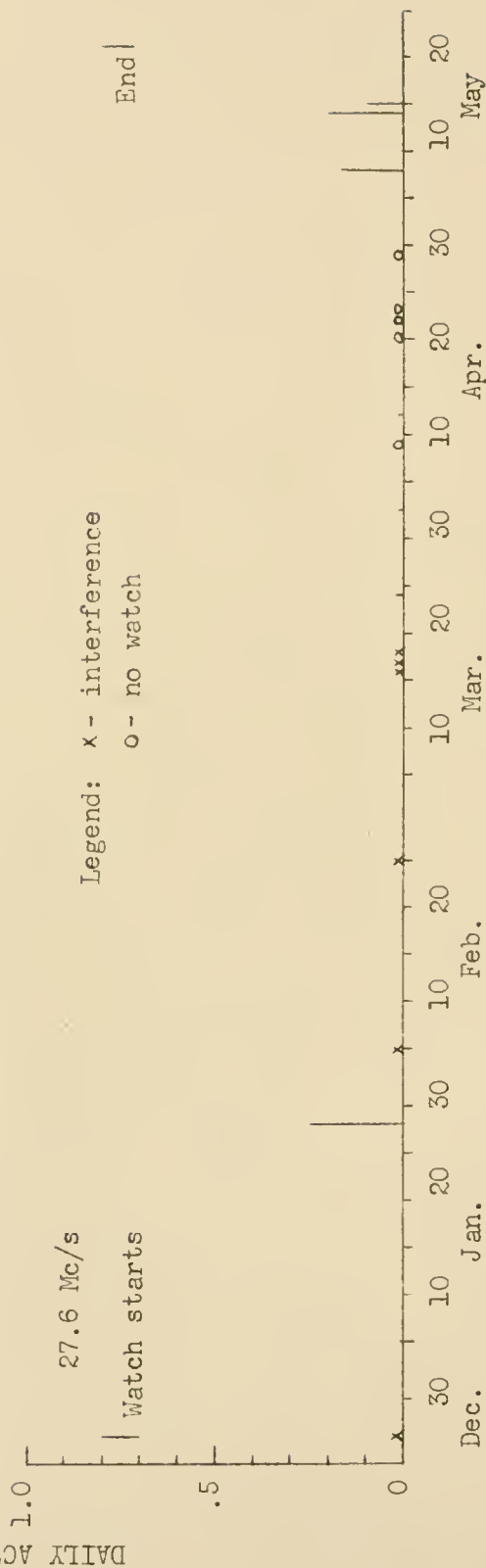
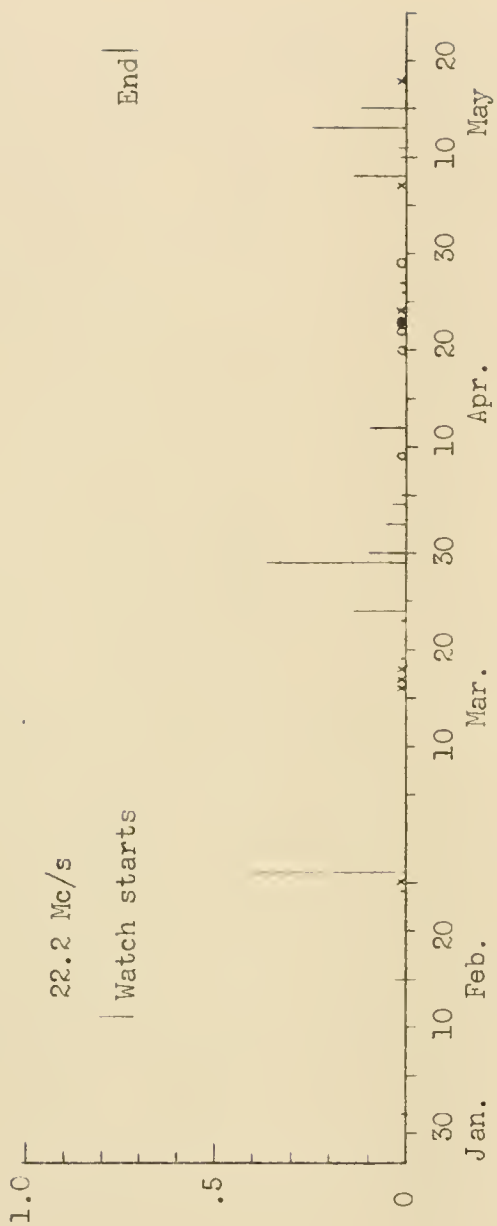


Figure 43.--22.2 Mc/s and 27.6 Mc/s activity plots of Florida 1960 data.

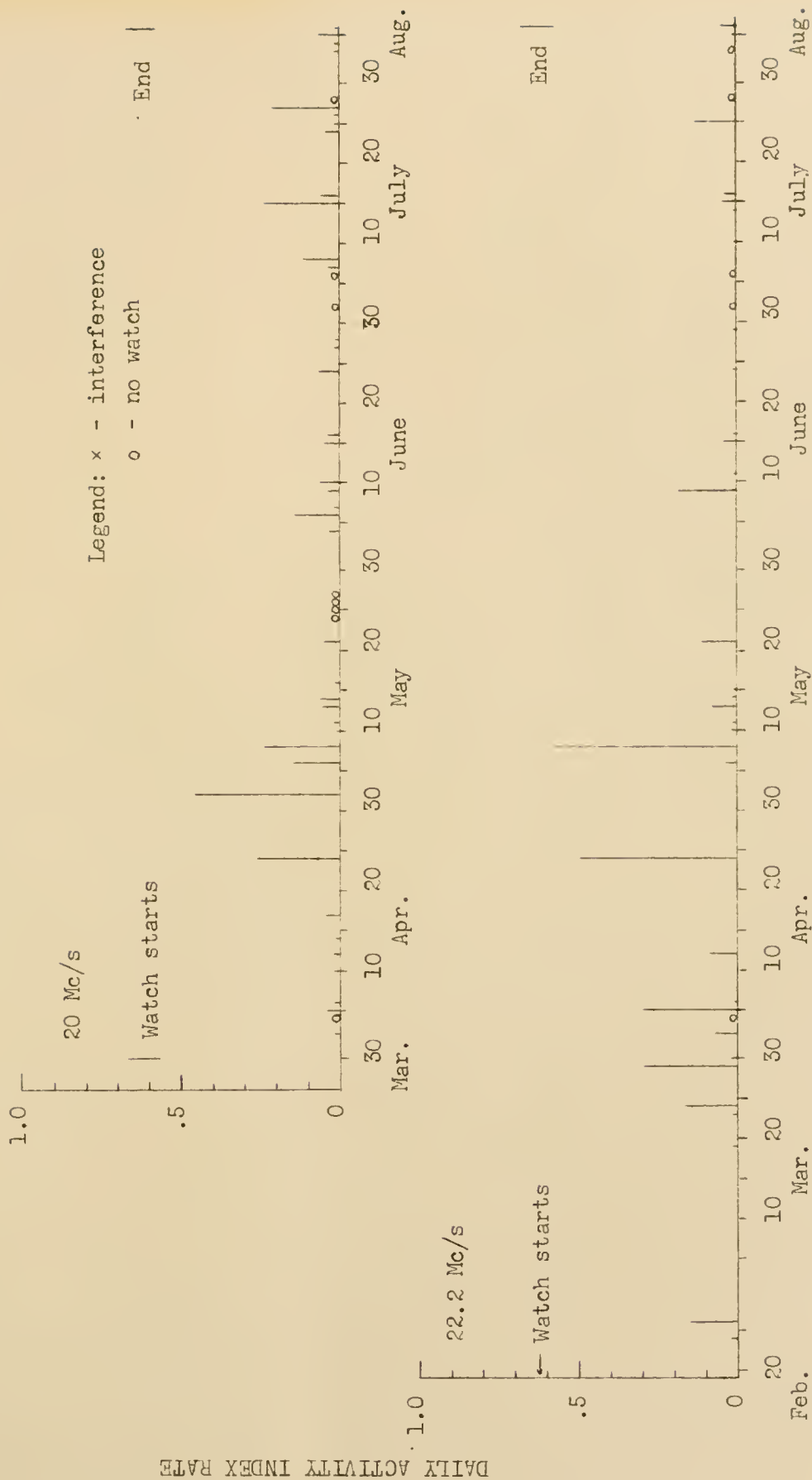


Figure 44.--20 Mc/s and 22.2 Mc/s activity plots of Chile 1960 data.

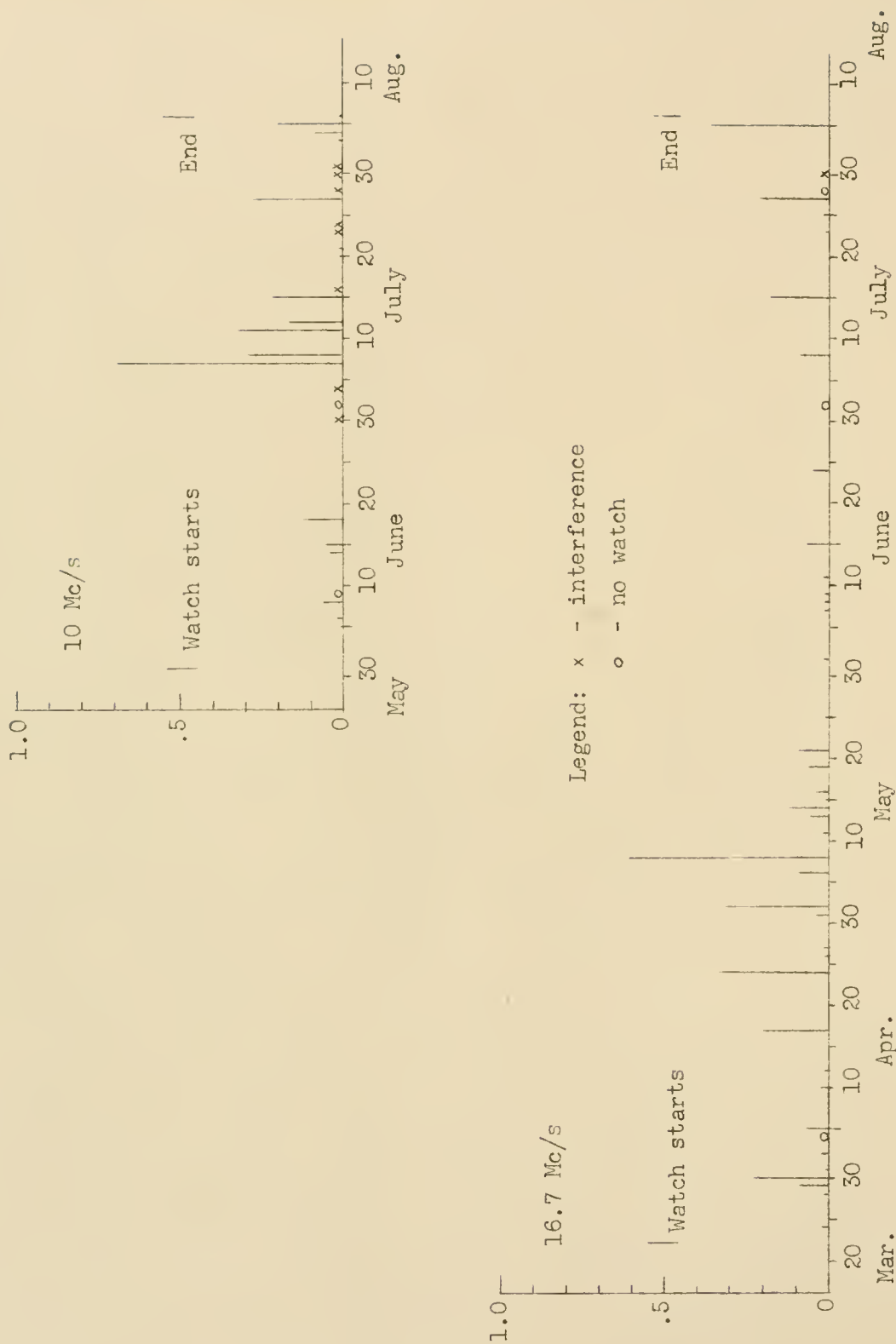


Figure 45.--10 Mc/s and 16.7 Mc/s activity plots of Chile 1960 data.

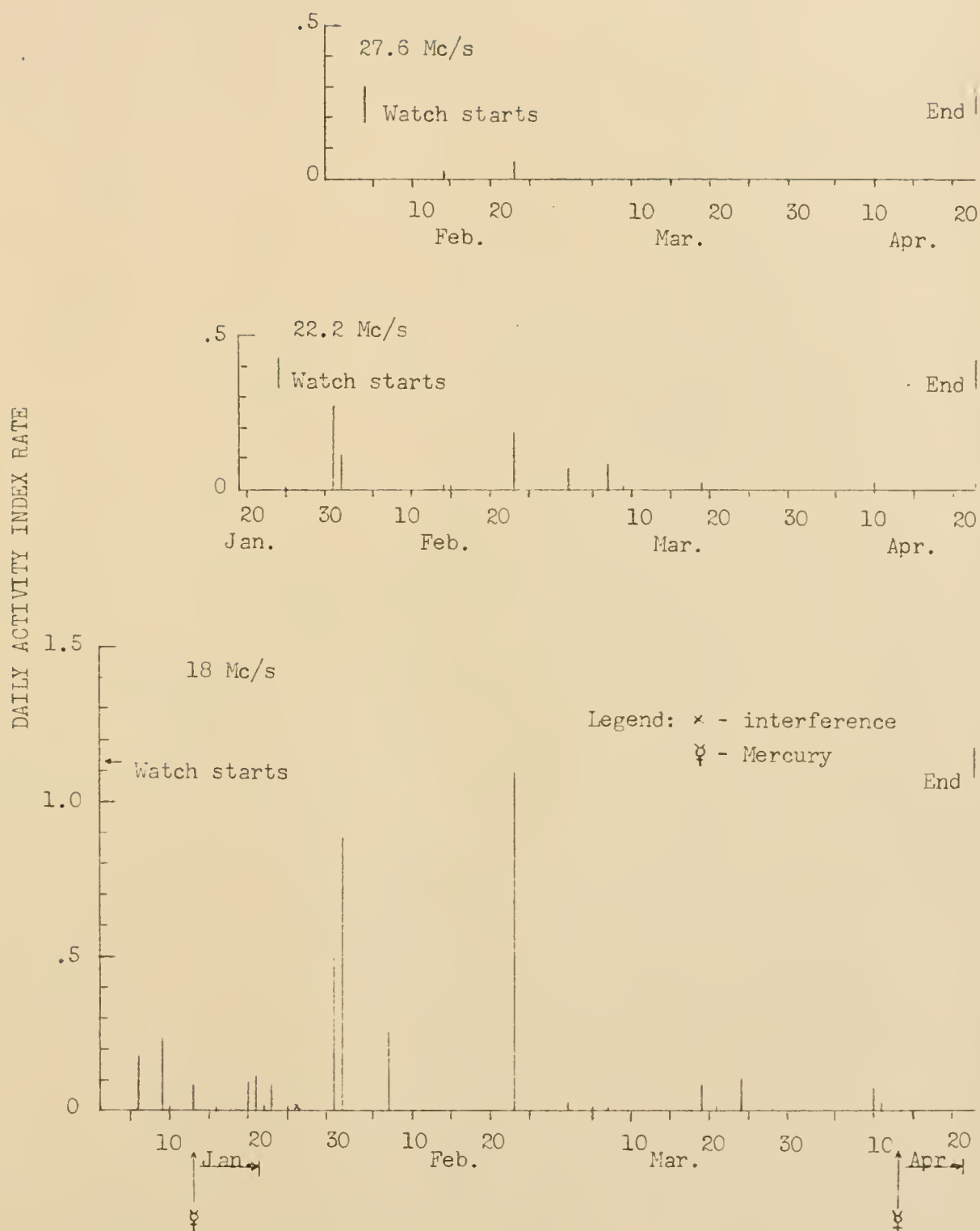
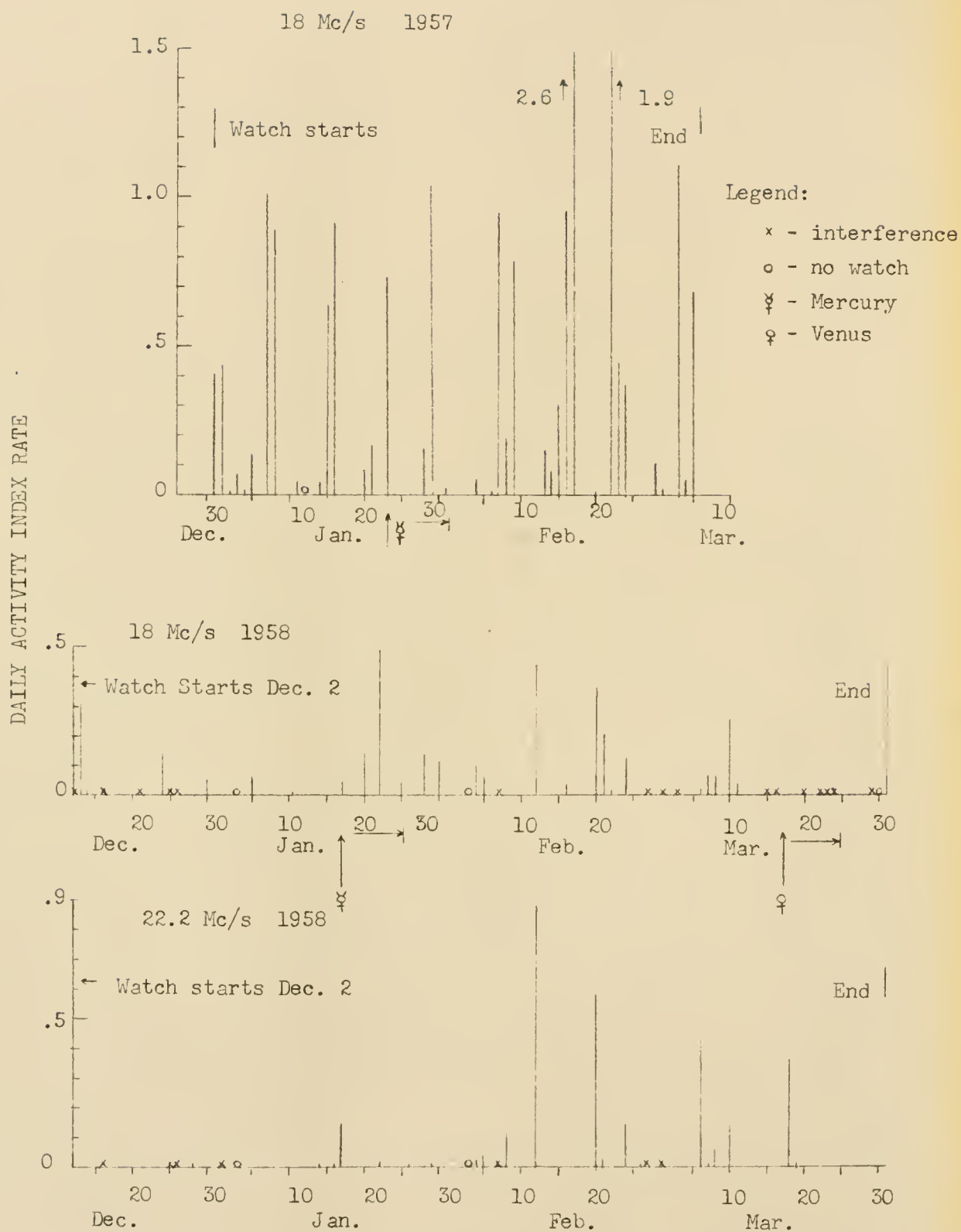
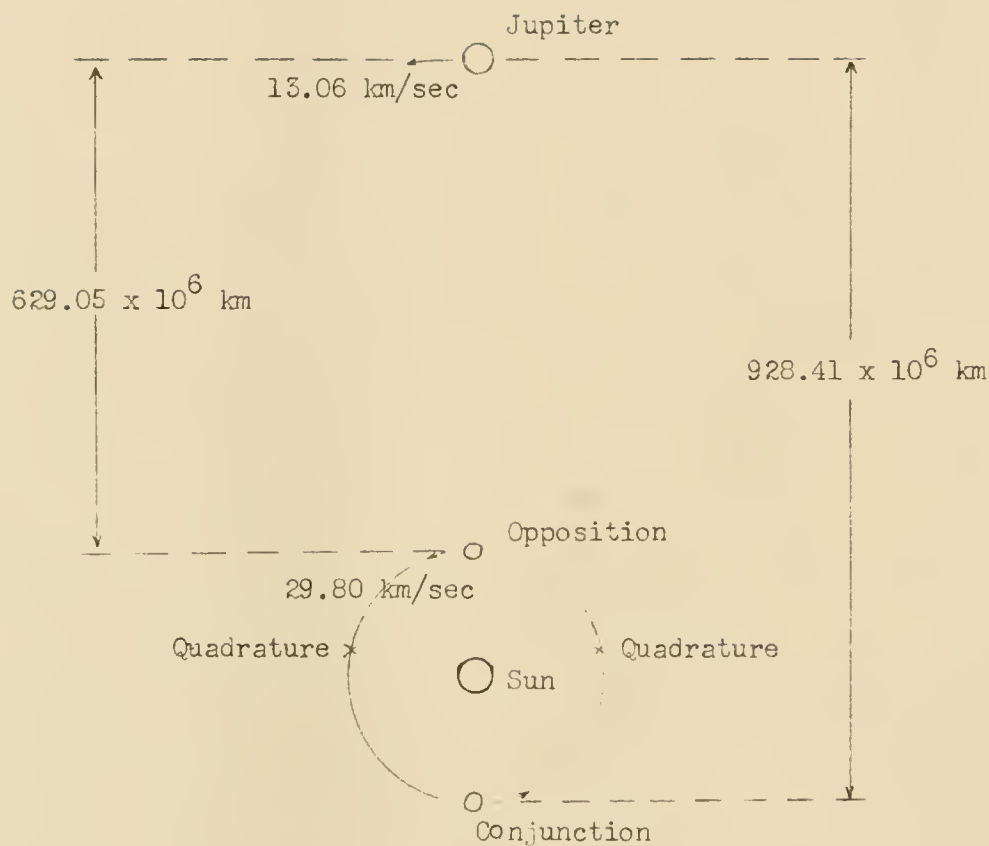


Figure 46.--Activity plots of Florida 1959 data.



ionosphere, they estimate a power gain of 1000 for this mechanism. They also point out that such focusing can cause a periodicity with rotation, assuming that Jupiter has a magnetic dipole inclined to the axis of rotation. By examining the data collected by Douglas (22), the Stroms have reported that there is a tendency for the storm durations to increase as Jupiter's apparent speed with respect to the background decreases. This, they mention, is evidence in favor of their ionospheric focusing theory.

Let us examine some of the consequences of a "Jovian magnetic lens" in the light of the data presented in the activity plots. When the angular rate of Jupiter as seen from the earth is a maximum, we should notice an increase in Jovian activity, for this is the time when Jupiter is sweeping past more radio sources per unit time. (The assumption of a background of numerous radio sources small with respect to Jupiter's apparent angular diameter is highly speculative, as the Stroms point out.) As shown in Figure 48, the greatest angular rate occurs at conjunction, when it is almost twice as great as the angular rate at opposition, where Jupiter is in retrograde motion. At points near quadrature the angular rate is zero and Jupiter activity should be at a low. Since more data was collected in 1961 than in any previous year, we shall search for the expected effects on the 1961 activity index rate plots. Conjunction of Jupiter occurred on January 5, 1961, and February 8, 1962. These dates are just off scale to the left and right respectively in Figure 35; however, notice that the activity index rate is a minimum at each end of the scale. Opposition occurred on July 25,



θ = angular rate of Jupiter with respect to the earth

$$\begin{aligned} \text{Conjunction: } \theta &= \frac{29.80 + 13.06}{928.41 \times 10^6} (57.3^\circ/\text{radian}) \\ &= 2.64 \times 10^{-6} \text{ }^\circ/\text{sec} \end{aligned}$$

$$\begin{aligned} \text{Opposition: } \theta &= \frac{29.80 - 13.06}{629.05 \times 10^6} (57.3^\circ/\text{radian}) \\ &= 1.53 \times 10^{-6} \text{ }^\circ/\text{sec} \end{aligned}$$

Figure 48.--Angular rate geometry.

1961, and the plot certainly implies that Jupiter was more active at this time than near conjunction. This is just the opposite of the effect expected if the ionospheric focusing theory explained the origin of the Jovian decameter radiation. Furthermore, on May 26 and September 24, 1961, at points near quadrature in Figure 48, the angular rate is zero, yet the daily activity index rate is far from being a minimum in the neighborhood of these dates as shown in Figure 35.

Now, let's examine another aspect of the Stroms' theory. Do we find, in our 1961 data, evidence that the duration of the storms increases when Jupiter's angular rate decreases? Figure 49 is a plot showing the duration of Jupiter's noise storms at 18 Mc/s, and the apparent angular rate of Jupiter, during the 1961 apparition. Again the dates of the conjunction of Jupiter are off the ends of the scale. At opposition, July 25, the duration of the storms should be much shorter than at the points near quadrature, May 26 and September 24, when the angular rate of Jupiter was a minimum. There is no evidence that this is the case in Figure 49. The duration of storms does not peak around May 26 or September 24. The Stroms have plotted "burst length in minutes" versus "seconds of arc per day" (32), using Jupiter data collected by Douglas (22). They point out that ionospheric effects influence the correlation, and this statement applies as well to the duration plot in Figure 49. Their figure contains 16 points, presumably representing 16 storms during the period 1957 - 1960. Figure 49 contains many times this number of Jovian storms. It is the conclusion of the writer that no systematic variation of storm duration with Jovian angular rate exists.

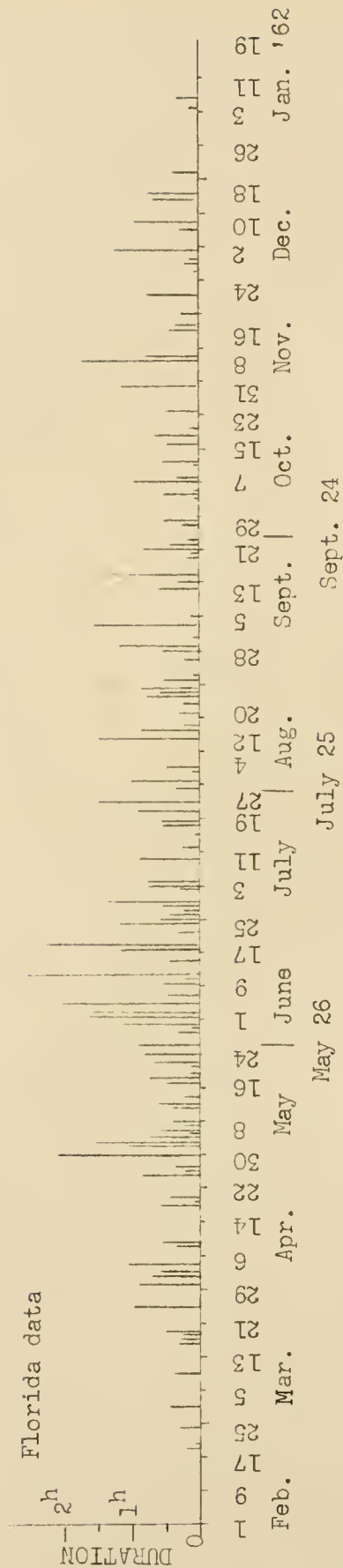


Figure 49.--The apparent angular rate of Jupiter as seen from the Earth in seconds of arc per day (top), and the duration of Jupiter's decameter storms at 18 Mc/s (below), during the 1961 apparition.

The Distance Effect

The Stroms have reported that an examination of data compiled by Gardner and Shain, Burke and Franklin, and Douglas, in the frequency range 18 - 20 Mc/s, revealed a tendency for the maximum number of bursts to occur when the Earth-Jupiter distance was about 5.4 A.U. This is a point in favor of their theory, since the focusing effect strongly depends on the orientation of the source and the magnetic field.

During the 1961 apparition of Jupiter, the 5.4 A.U. spacing between the Earth and Jupiter occurred on April 3 and November 19. Examination of the 18 Mc/s combined activity plot in Figure 39 shows that Jupiter was relatively inactive in the neighborhood of these dates, i.e., from March 28 (spacing 5.5 A.U.) to April 10 (spacing 5.3 A.U.), and from November 12 (5.3 A.U.) to November 27 (5.5 A.U.). The dates of greatest activity are June 5, 24, and August 12, when the Jupiter to Earth distance was 4.45, 4.24, and 4.14 A.U., respectively. After inspecting the activity plots, I find no two periods of enhanced Jupiter activity which are symmetric about the July 25th opposition suggesting any distance effect such as that reported by the Stroms. Regarding the 1961 data obtained by the Florida group, I would like to point out that this was the first time Jupiter had been systematically observed for twelve consecutive months.

As with all other theories that have been postulated to explain the origin of the Jovian decameter bursts, the ionospheric focusing theory has a difficult time accounting for the longitude dependence of the radiation. If Jupiter has a magnetic dipole moment which is

inclined 9° with respect to the axis of rotation, as the microwave data suggest, this hardly seems to be enough to explain the observed histogram peaks shown earlier in this chapter. To radio sources in the background, Jupiter's magnetic field would appear almost axially symmetric. Also, it is hard to believe that storms occurring simultaneously on different frequencies can be accounted for by assuming separate focusing mechanisms operative above and below the Jovian layer of maximum electron density. The terrestrial ionosphere varies greatly under the influence of solar ultraviolet radiation and bombardment by solar plasma spewed forth from the sun during periods of enhanced solar flare activity. It is presumed that a Jovian ionosphere would be influenced by the same effects. Jovian decameter storms often occur at several frequencies simultaneously, and the writer feels that a theory of origin connected with a presumably varying Jovian ionosphere cannot explain the observed constancy in the dynamic spectrum of the Jovian radiation (see Warwick - reference 29). Furthermore, Dr. A. G. Smith has recently mentioned that the spectral index of the Jovian decameter emission (which T. D. Carr of this Florida group has found to be approximately -3.6) is much smaller than the indices of the discrete sources, which generally range from -0.3 to -2.2 (33). Again it does not appear that Jupiter is merely focusing energy from discrete sources in the background.

From the studies described in this and the preceding section, the writer concludes that the ionospheric focusing theory of the Stroms does not look very promising as an explanation of the Jovian decameter radiation.

The Elongation Effect

For several years the Florida group has been aware that at the beginning of the Jupiter observing seasons, very little decameter radiation is received, and that as the season progresses, Jupiter seems to become more active. The frequency of reception of the Jovian bursts reaches a general maximum around opposition and then tapers off again to almost nothing toward the end of the apparitions. In 1960, Douglas wrote (22), "The average occurrence probability function seems to depend in some way on the elongation of Earth as seen from Jupiter, or on some quantity correlated with that elongation." At first, it was thought that poorer listening conditions caused this effect. Generally, the apparitions begin when the Earth is in eastern elongation as seen from Jupiter. The watches are then only a couple of hours long and are terminated by sunrise effects in the ionosphere. Near opposition, Jupiter is on the meridian at local midnight and the watches are six to eight hours in duration. Toward the end of the apparition when the Earth is in western elongation as seen from Jupiter, the watch periods come in the evening hours when the ion density in the ionosphere is still far from the minimum in the diurnal cycle, and listening conditions are quite poor.

A closer study of the variation in Jupiter activity with elongation reveals that observing conditions are not the cause of this effect. In Figure 50 the monthly activity index rate is plotted for three frequencies monitored at the Florida station in 1961. Notice that the 18 Mc/s and 22.2 Mc/s curves show a general maximum in the center and

a decline in Jovian activity at the beginning and end of the apparition. The 27.6 Mc/s plot does not show much detail because it is based upon a comparatively small amount of data collected at this higher frequency. The elongation of Jupiter is plotted above the activity graph in Figure 50. At opposition, the elongation is 180° ; at conjunction, 0° . The observations during the 1961 apparition lasted longer than in any previous year, and yet they did not cover a complete elongation cycle.

The variation in Jupiter activity with elongation cannot be explained away by blaming the effect on listening conditions. The same factors involved in the monthly activity index rate calculation are used in the determination of the daily activity index rate, but in the former, the summation is carried over all the activity and listening periods in a month. The duration of the listening period is in the denominator of this sum; hence, we divide out the effect of observing conditions. Around opposition, when the watch periods are long, this factor in the denominator will decrease the value of the monthly activity index rate, yet we notice the curves still exhibit a maximum here. Another factor which enters into the calculation is the intensity of the Jovian storms. This quantity in the numerator of the sum is larger around opposition, since the flux density of the radiation at opposition should be approximately 2.2 times the flux density at conjunction, assuming that the inverse square law holds. In order to remove the variation in intensity with Earth-Jupiter distance, all of the activity values have been corrected to correspond to a distance of five astronomical units. It seems that a combination of effects, many of which are not understood, is producing the variation in Jovian activity with elongation.

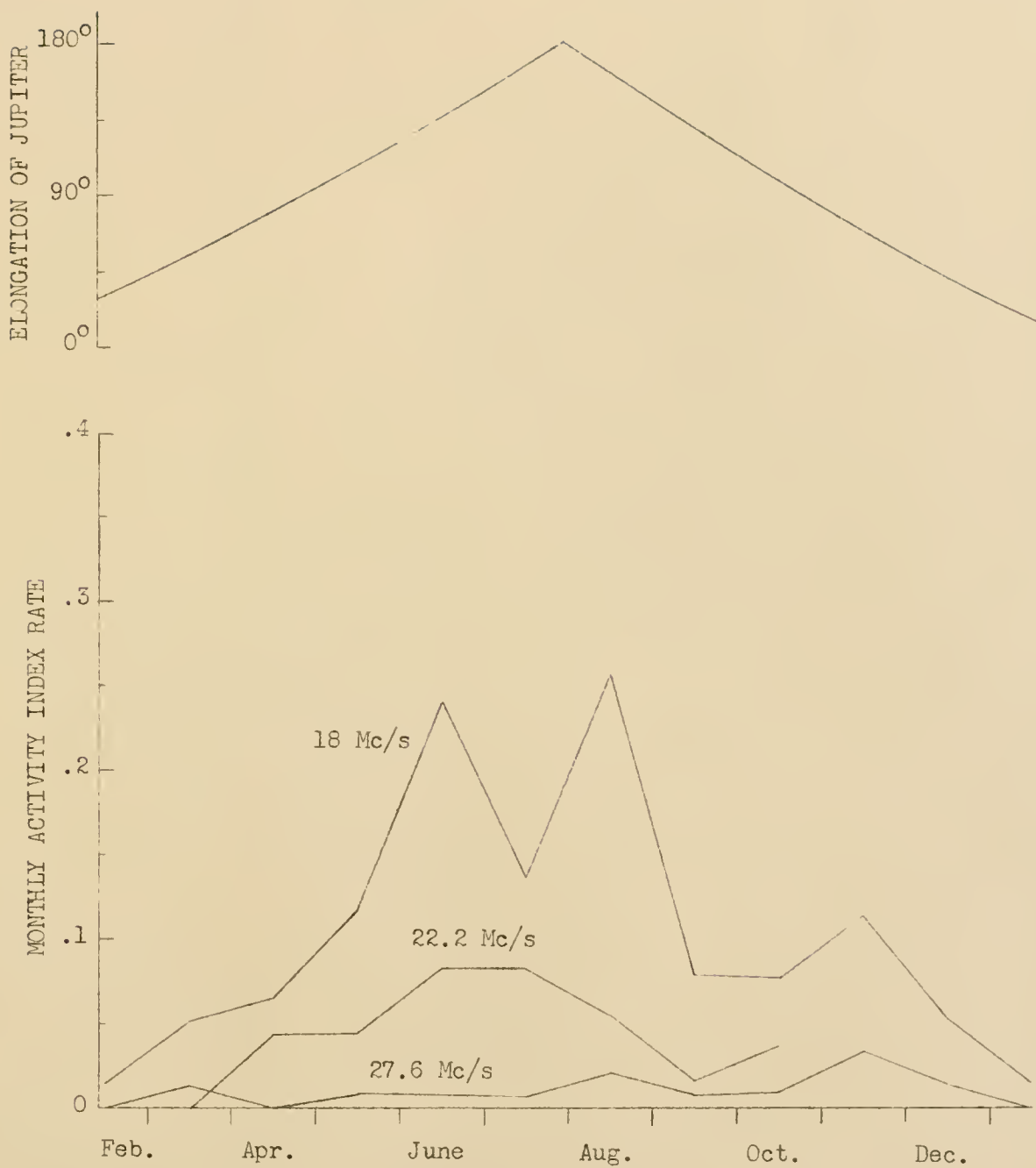


Figure 50.--1961 Florida data showing the elongation effect. The activity values have been adjusted to correspond to an Earth-Jupiter distance of 5 A.U.

Figure 51 contains the monthly activity index rate plots of the 1961 Chile data, corresponding to an Earth-Jupiter distance of 5 A.U. We see the same variation with elongation of Jupiter. Notice the slight dip in the 15, 18, 20, and 22.2 Mc/s curves at opposition. This dip is also evident on the 18 Mc/s plot of the Florida data in Figure 50. A possible explanation for this local minimum around opposition will be discussed in the next section of the text.

Figure 52 contains monthly activity index rate plots of the 18 Mc/s and 22.2 Mc/s data back through 1957. These curves have been standardized to correspond to a 5 A.U. planetary separation. Again, a curve showing the elongation of Jupiter is included for comparison. The abscissas of the activity plots show the extent of the observation periods, and lie directly above the parts of the elongation cycle that correspond to those apparitions. All of the Jupiter data used in constructing these curves were collected at the Florida station except the data for the 1961 22.2 Mc/s plot. In this one exception the Chile data is believed to be more reliable, because of equipment failure in the 22.2 Mc/s polarimeter system in Florida. The same general maximum around opposition as was noticed on the 1961 plots also shows up on the 1957 and 1960 curves. The 1958 and 1959 apparitions did not extend far enough into the elongation cycle to show this effect. It looks as though the 1958 curves might be approaching a maximum toward opposition, but the 1959 curves are descending. These were both bad years for receiving Jovian radiation and very little data was collected. Note that the ordinate scale on the 1957 curve has been shifted. Again notice the dip

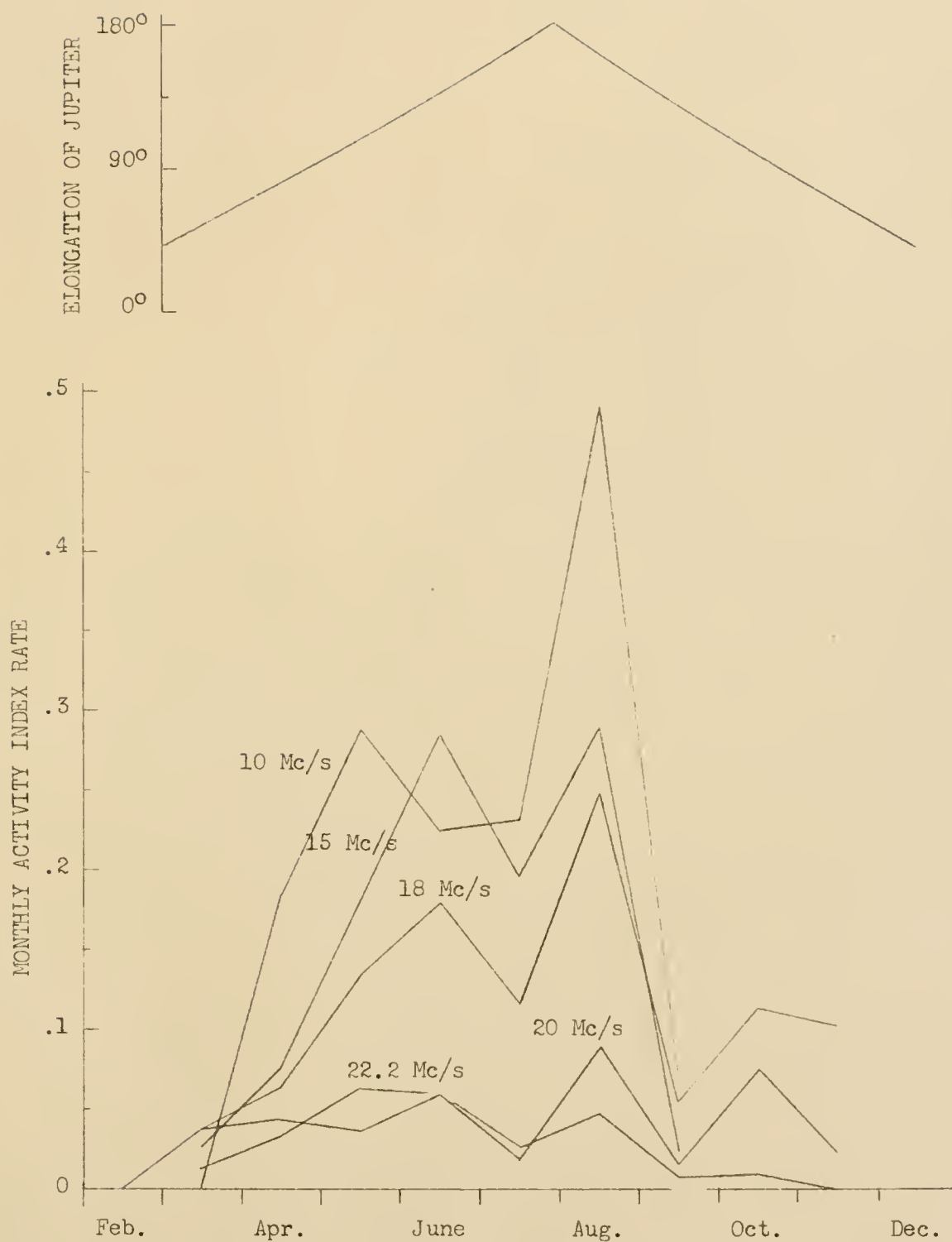


Figure 51.--1961 Chile data showing the elongation effect. The activity values have been adjusted to correspond to an Earth-Jupiter distance of 5 A.U.

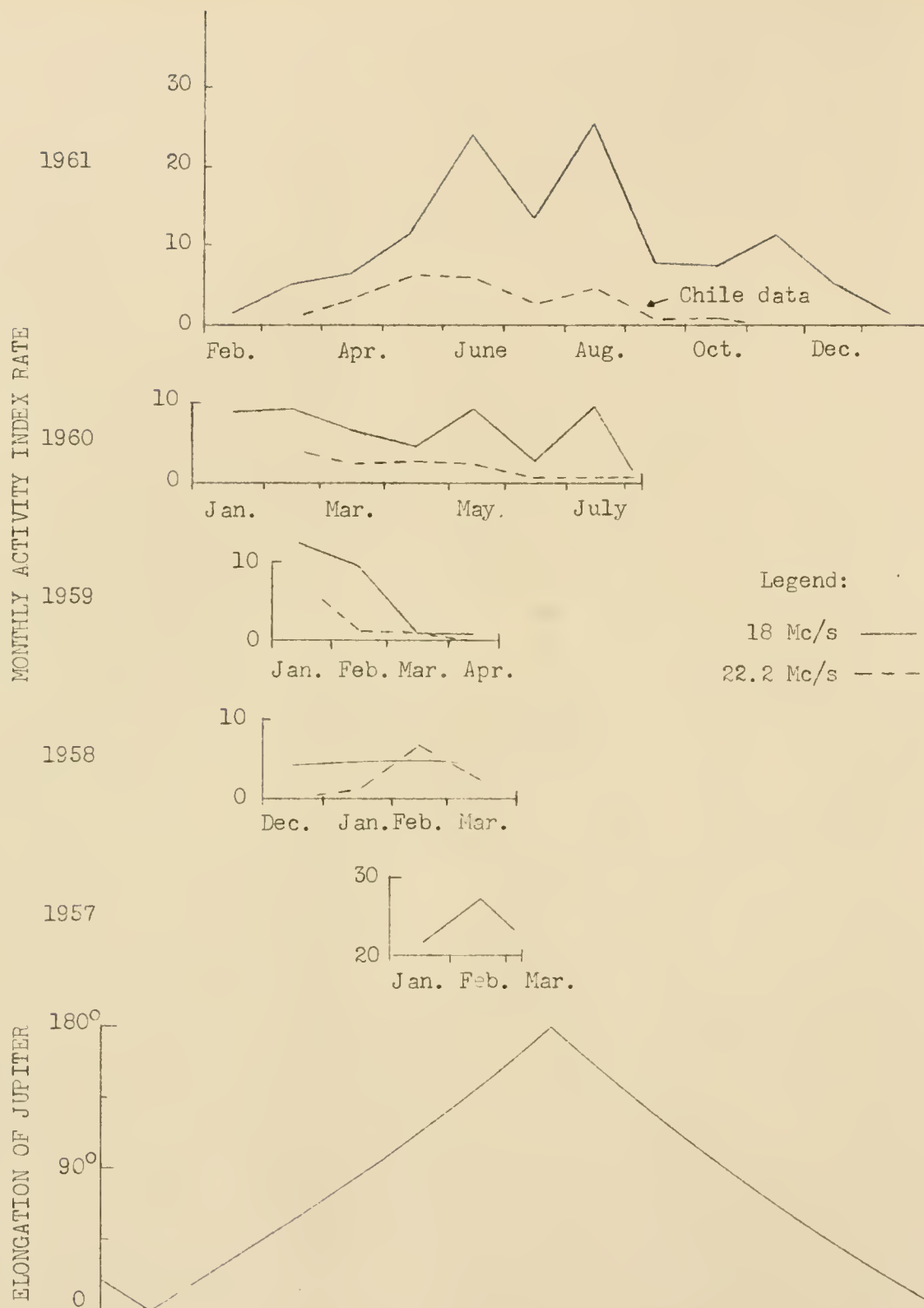


Figure 52.--Elongation effect during 1957 - 1961. All curves are from the Florida data except the 1961 22.2 Mc/s curve. Activity values have been standardized to 5 A.U.

or local minimum at opposition; this is apparent on the 1957 plot, the 1960 18 Mc/s curve, and the 1961 18 Mc/s and 22.2 Mc/s curves.

Evidence of Particle Stream Deviation by the Earth's Magnetosphere

The writer suggests that the decrease in Jupiter activity around opposition which is evident in Figures 50, 51, and 52 is caused by the deflection of solar plasma by the earth's magnetosphere. The underlying assumption is that the Jovian decameter radiation depends in a fundamental way on the streams of charged particles flowing outward from the sun's corona.

Recent satellite and space probe measurements have confirmed that solar plasma flows around a certain volume containing the earth and its magnetic field (34). A plasma probe on Explorer 10 detected a cold plasma which seemed to be at rest with respect to the earth out to a distance of 21.5 earth radii, in a direction about 45° from the anti-solar direction. Suddenly the satellite seemed to burst out into the interplanetary plasma (35). Magnetometers measured a field that suddenly changed in direction and strength, and the plasma probe detected a stream of protons from the sun having a velocity of about 3×10^2 km./sec. and a density of about 10 particles/cm³.

Figure 53 shows sections of the earth's magnetosphere (a, b) and its surface lines of force (c). These diagrams were obtained from reference (36). Since the inferred velocity of the front of a solar stream is of the order of 10^3 km./sec. (37), and the hydromagnetic wave velocities in the magnetosphere decrease outward (38, 39), at some

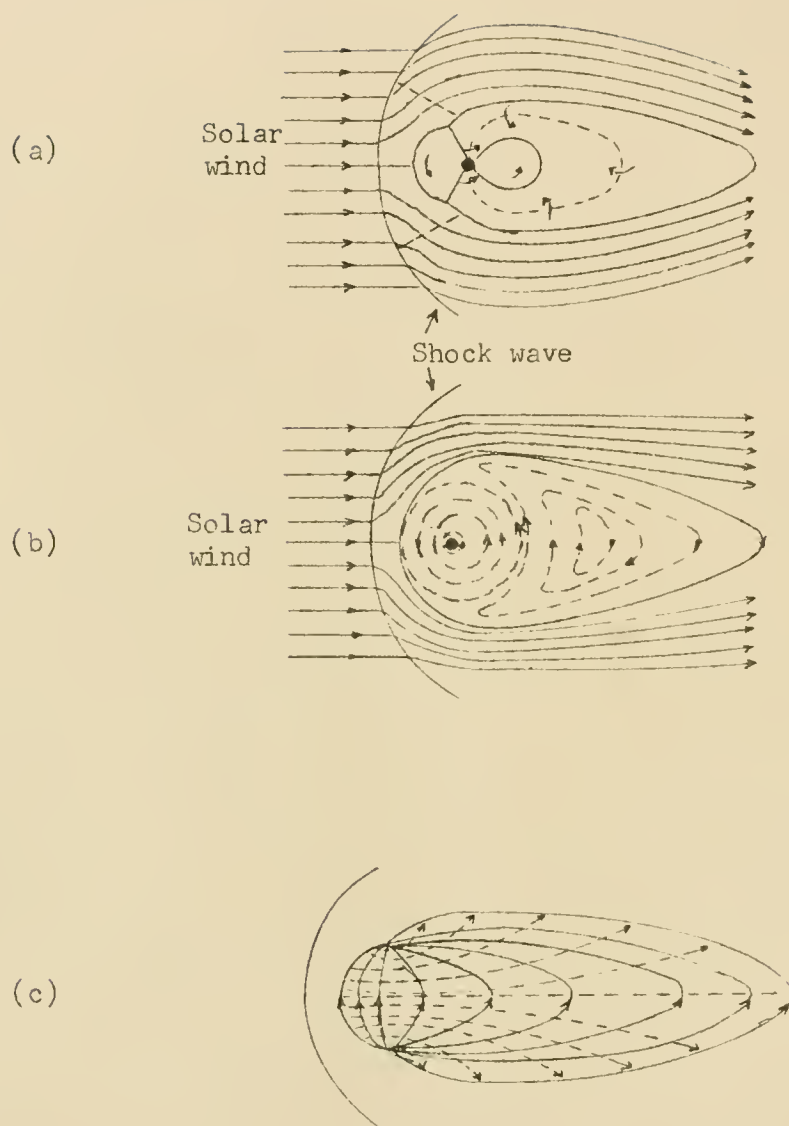


Figure 53.--The earth's magnetosphere (taken from reference 36). (a) Shows a section in the plane containing the geomagnetic axis and the solar wind direction. (b) Shows the north polar view of a section in the geomagnetic equatorial plane. Both diagrams show the bow shock wave and the stream lines of the solar wind. The sense of rotation of the magnetosphere is indicated by the short arrows. The small black dot is the earth. (c) Is an elevation view showing the surface lines of force (solid) and the surface currents (dashed). North is at the top.

distance the solar stream front compresses the magnetosphere faster than the local hydromagnetic wave velocity. A shock wave is formed and its position, calculated by treating the interplanetary plasma as a perfect gas, is shown in Figure 53. Diagrams (a) and (b) are sections of the magnetosphere in the plane containing the geomagnetic axis and the solar wind direction and in the plane of the geomagnetic equator. Notice how the earth's magnetic field is confined to a tear-drop-shaped cavity by the solar wind. The short arrows indicate the direction of rotation of the magnetosphere. Diagram (c) is an elevation view showing the lines of force (solid lines) and the currents (dashed lines) on the surface of the magnetosphere. Notice that the lines of force on the downstream side are roughly in the sun-earth direction except near the equatorial plane. The geomagnetic tail may extend to 60 earth radii, at times encompassing the moon. These pictures are consistent with the data obtained by Explorers 10 and 12. The effects of inclination of the magnetic axis with respect to the axis of rotation have been neglected.

Figure 54, obtained from reference (40), shows a close-up of the cavity carved out of the solar stream by the earth and its magnetic field. The cavity boundary varies, for besides the relatively constant pressure of the solar wind, consisting of low energy protons and electrons that are continuously emitted by the sun, it is also influenced by solar storms that produce streams of high energy particles. This was verified by Explorer 10, which measured proton velocities varying from 2 to 7×10^2 km./sec. and densities from 5 to 10 particles/cm³ (41). Explorer 12 (launched August 15, 1961) measured the extent of the

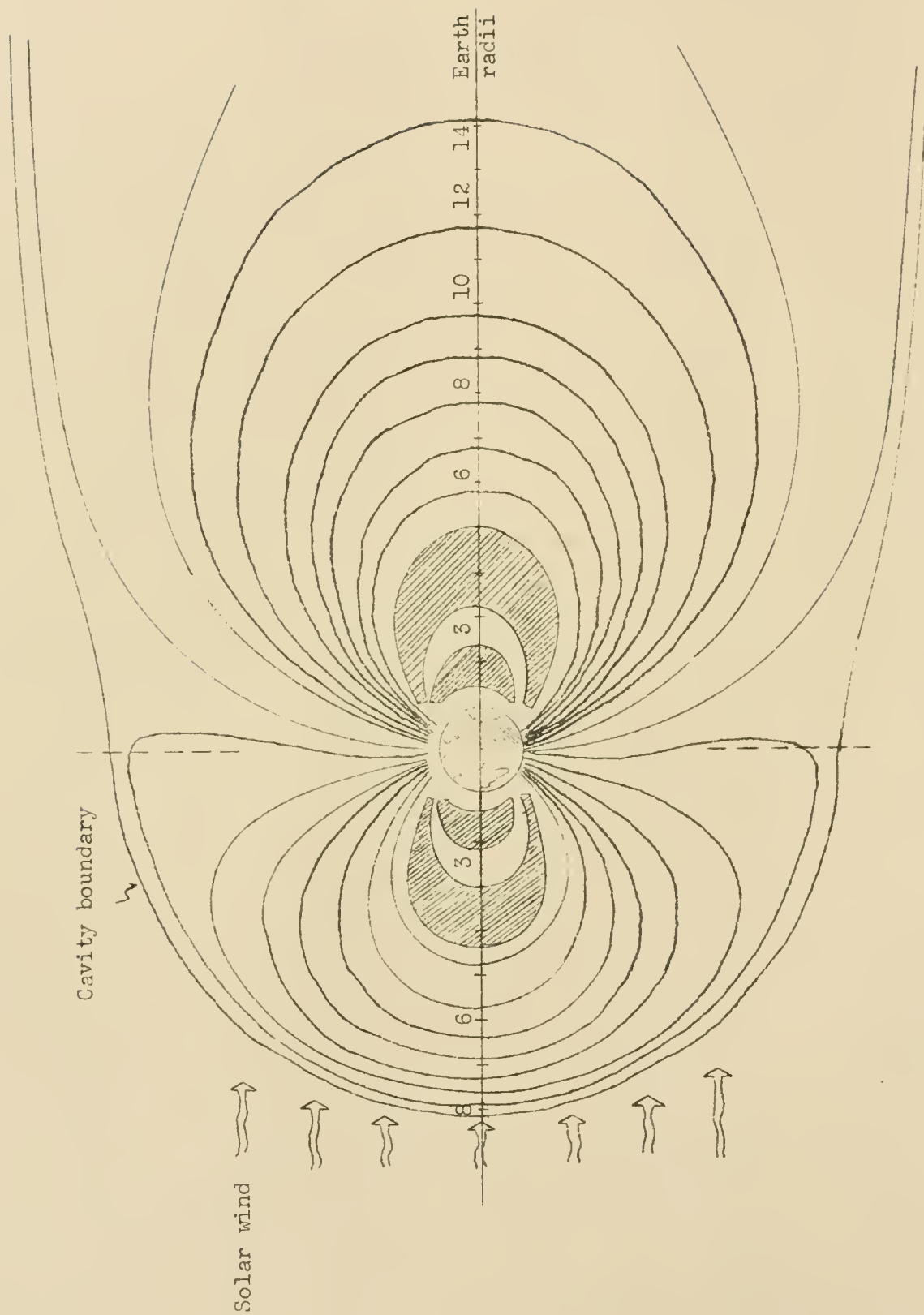


Figure 54.--Cavity carved out of the solar stream by the earth.

magnetosphere on the sunlit side and found that it varied with solar activity. Explorer 10 (launched March 25, 1961) passed through the cavity boundary at the lower right-hand corner of Figure 54 and discovered the draping effect of the earth's magnetic field on the dark side. Notice that the Van Allen belts are unsymmetrical because of the solar wind. Pioneer 1 (launched October 11, 1958) found that the magnetic field intensity falls off as r^{-3} out to 27,000 miles with no regular behavior beyond that point. It also determined that there is a relatively disturbed transition between the earth's magnetosphere and the magnetic field of interplanetary space, which is of the order of 5 to 10×10^{-5} gauss. It has been suggested that the shock wave pictured in Figure 53 could account for the turbulent structure of the distant magnetic field.

Returning to the evidence at hand, we notice that when the Earth is between the Sun and Jupiter, the decameter activity of the giant planet declines. The 1961 Florida data at 18 Mc/s show this (see Figure 50). The 1961 Chile data at 15, 18, 20, and 22.2 Mc/s show this (see Figure 51). And, the 1960 Florida data at 18 Mc/s show this (see Figure 52). In Figure 50, the monthly activity index rate plots of the 22.2 and 27.6 Mc/s data do not exhibit a dip around opposition; however, only a small amount of radiation was received at 27.6 Mc/s, and equipment failures plagued the 22.2 Mc/s polarimeter system in Florida during the 1961 apparition. For these reasons, the latter two monthly activity plots are not as reliable as the 18 Mc/s graph. Of the 1961 Chile data in Figure 51, only the 10 Mc/s plot fails to show a decrease

in Jovian activity near opposition, and I cannot find an obvious explanation for this. Figure 52 contains the 18 and 22.2 Mc/s data back through 1957. The 18 Mc/s plot of the 1960 data shows the dip at opposition. The 1960 22.2 Mc/s plot shows very little detail due to the scarcity of data. In 1959 and 1958 the apparitions stopped short of opposition, so we have no check on the effect for these years. In 1957, although the observing season ended two weeks prior to opposition, the monthly activity plot shows a downward trend, lending support to the idea of screening by the earth's magnetosphere.

Deflection of solar particles by the earth's magnetic field is not a new idea. In 1954 Slipher and Wilson (42) pointed out that eclipses of the sun by the earth's magnetic field could explain the clearing of the Martian blue haze at opposition. They suggested that the haze is caused by bombardment of the Martian atmosphere by solar protons, and that at opposition the streams of protons are deviated by the earth's magnetic field. More recently, Sagan (43) has argued that the proton flux and energies required to produce the observed blue haze are much greater than the space probe measurements indicate actually exist. He also points out that the durations of the blue haze clearings greatly exceed the computed duration of such an eclipse.

Thus far, we have been examining monthly activity index rate plots. Can we gain any information from the daily activity plots of the periods around opposition? Figure 55 shows the variation in the daily activity index rate during the 61-day periods centered on the 1960 and 1961 oppositions of Jupiter. Both plots were constructed from

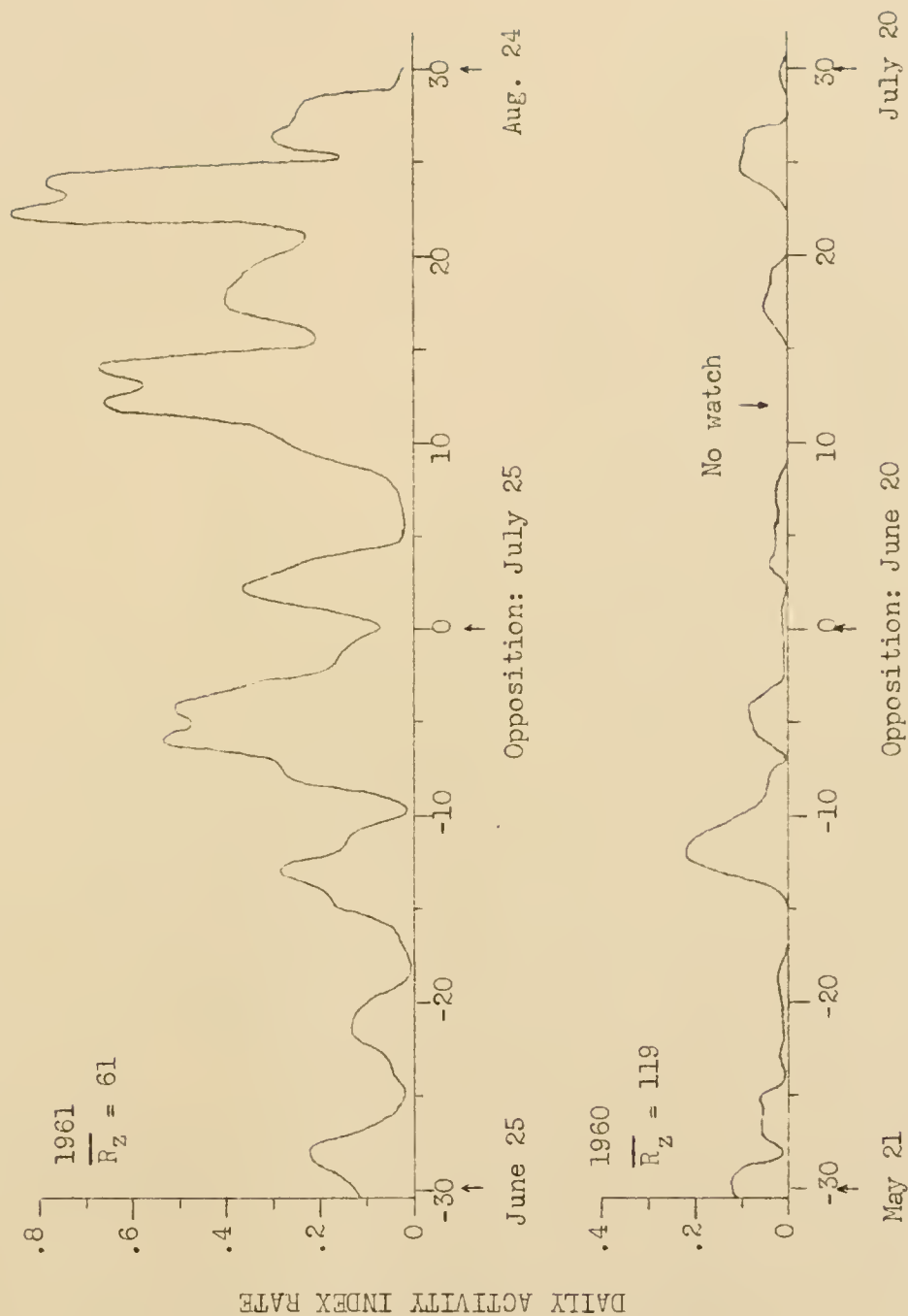


Figure 55.--Variations in Jupiter activity at the Chile station on 18 Mc/s during the period from 30 days before to 30 days after opposition. Both the 1961 and the 1960 curve have been smoothed by three point averaging. $\overline{R_z}$ is the average Zurich sunspot number for the period covered by the plot.

18 Mc/s data collected in Chile, and the curves have been smoothed by three-point averaging. Notice the four eight-day cycles in Jovian activity preceding opposition on the 1961 curve. This periodicity is reminiscent of the data of the 1957 apparition, all of which preceded the Jovian opposition of that year. The 1960 curve does not show this effect.

Since Jupiter is normally active for two - four days and then quiet for several days, the curves are characterized by an unevenness which is due to the bunching of the Jovian radiation. For this reason, the writer feels that the monthly plots are a better indication of the screening effect of the Earth's magnetosphere, since they smooth out the daily variations in Jupiter activity. (We must remember that we are dealing with a sporadic source.) The 1961 curve may indicate a general minimum preceding opposition by as much as 20 days. The 1960 curve shows nothing. The average Zurich daily sunspot numbers for the periods of the plots are given since any screening effect should be more pronounced during periods of low solar activity when there is less ultraviolet radiation to cover up what we are looking for.

The next logical question is, do we find a decrease in Jupiter's activity at zenocentric inferior conjunctions of Mercury, Venus, or Mars? First, we probably should inquire about the existence of magnetic fields on these planets. The only known investigation of such magnetic fields was a study by J. Houtgast (44). After examining the variation in the Earth's magnetic character figures during the 100-day periods centered on 44 inferior conjunctions of Venus since 1884,

he concluded that there was a marked decrease in the Earth's magnetic activity from seven days before to one day after conjunction, implying deflection of the solar corpuscular stream by Venus' magnetic field.

A survey of the Jupiter data collected by the Florida radio astronomy group since 1957 revealed that three zenocentric inferior conjunctions of Venus occurred during Jupiter decameter observing seasons. Figure 56 contains the daily activity plots covering the periods around conjunction in 1958, 1960, and 1961. We are forced to examine the daily activity index rate plots, because the elongation effect previously discussed is the prominent variation on the monthly activity plots. The Florida 18 Mc/s data were used to construct the curves of Figure 56. The zero-day marks the zenocentric inferior conjunction of Venus and the curves have been smoothed by three-point averaging. $\overline{R_z}$ is included to indicate the degree of solar activity. The 1958 curve is of little value because the conjunction occurred at the end of the apparition. In 1960 there seems to be a dip in the Jovian activity on each side of the February 23rd conjunction. The 1961 curve shows something of a dip in the decameter activity around conjunction, although it is not very convincing. On the basis of the evidence presented, no conclusions can be drawn regarding the screening effect of a Venusian magnetic field. It would be well to keep in mind two factors which strongly influence the effect we are searching for: (1) the solar plasma clouds appear irregularly, and (2) Jupiter is an intermittent source of decameter radiation.

In Figure 56 we again see evidence of a cyclic behavior. The 1960 plot shows four eight-day cycles beginning with the -28th day. The 1961 curve shows three seven-day cycles starting with the zero-day. It has been suggested (28) that these cycles might be evidence of Jovian ionosphere oscillations caused by the tidal effects of Jupiter's largest satellite Ganymede, whose period is 7.17 days. Although the theoretical tide-rising force of Ganymede is not as great as that of the two closer Galilean satellites, a resonant effect might permit it to dominate the atmospheric tides, as in the case of solar tides in certain regions of the Pacific Ocean and in the earth's atmosphere.

There was only one zenocentric inferior conjunction of Mars coinciding with Jupiter observations, and it occurred at the very beginning of the 1960 apparition. For this reason, it is not plotted here.

Figure 57 shows the variation in Jupiter activity around zenocentric inferior conjunctions of Mercury. (a) is a plot of the average daily activity index rate for 11 conjunctions. (b) is a plot of the average daily activity index rate for the four conjunctions during 1961 when the average daily sunspot number for each of the four 21-day periods was less than 70. Table 7 gives the dates of zenocentric inferior conjunctions of Mercury which coincide with Jupiter observations and the average Zurich daily sunspot number for each 21-day period. Plot (a) does not show a decrease around the zero-day. Plot (b), obtained by averaging the daily activity index rate values for the four

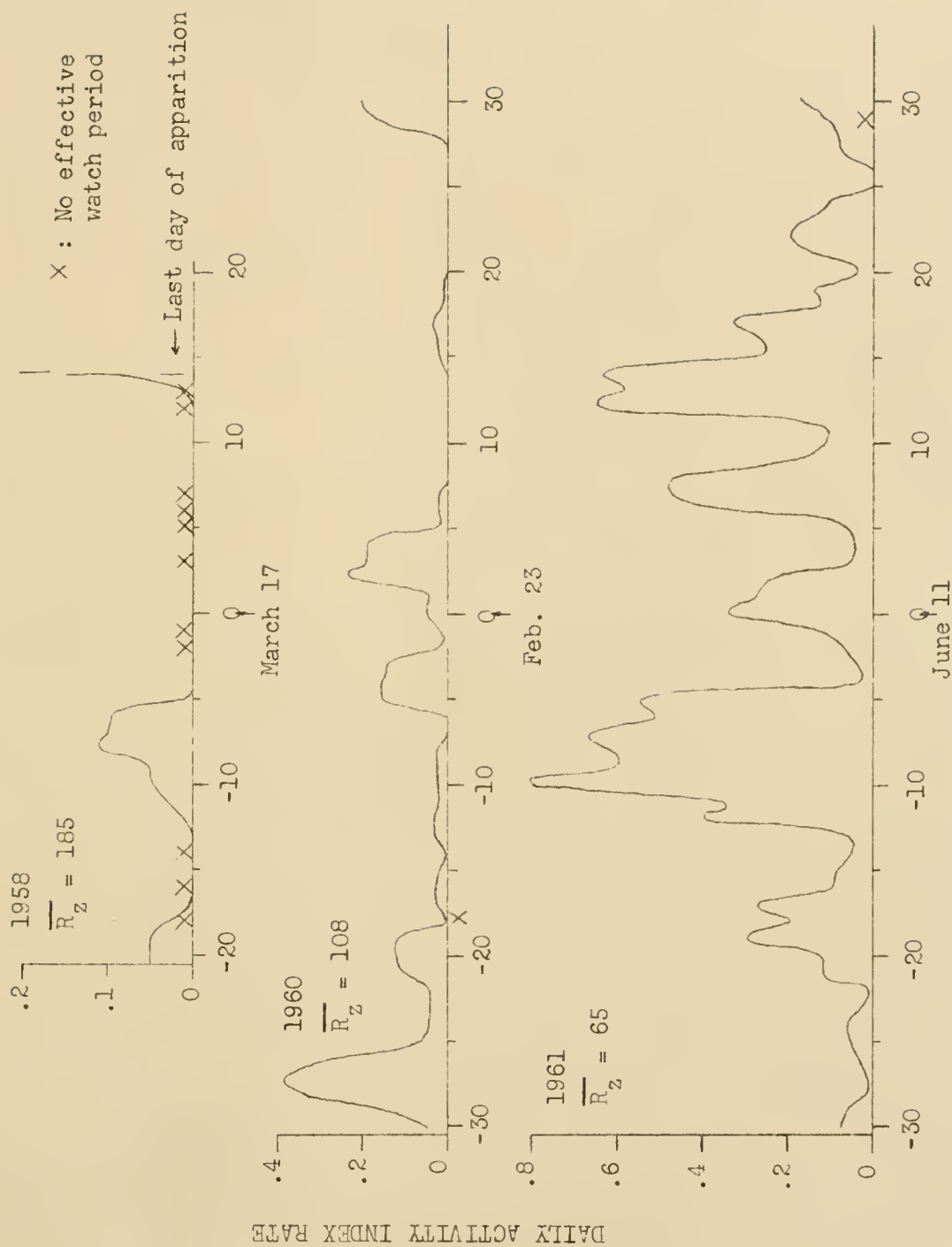


Figure 56.--Variation in Jupiter activity around zencentric inferior conjunction of Venus.

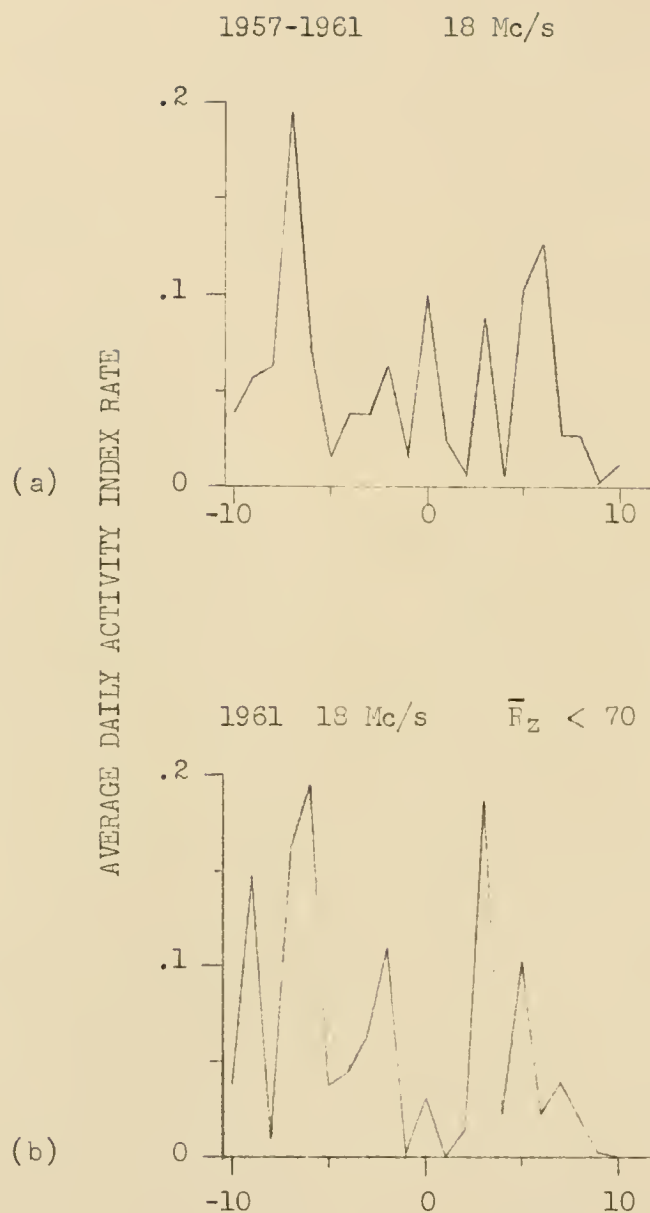


Figure 57.--Variation in Jupiter activity around zenocentric inferior conjunction of Mercury. (a) is the average of eleven inferior conjunctions during the 1957 through 1961 apparitions. $\bar{R}_Z$ for the eleven 21-day periods ranged from 35 to 215. (b) is the average of the four inferior conjunctions during the 1961 apparition. $\bar{R}_Z < 70$ for all four 21-day periods. The Jovian activity index rate values were obtained from 18 Mc/s data.

zenocentric inferior conjunctions of Mercury for which $R_z < 70$, shows a dip centered on the zero-day. The evidence is not very conclusive. It is important that a check on this effect be continued through the period of sunspot minimum. There is some question as to the existence of a magnetic field on Mercury, since the planet probably does not have a liquid core (44).

TABLE 7

Zenocentric Inferior Conjunctions of Mercury

Date	$\overline{R_z}$
January 23, 1957	131
January 17, 1958	215
January 13, 1959	209
April 13, 1959	148
January 9, 1960	130
April 9, 1960	133
July 9, 1960	131
April 6, 1961	67
July 6, 1961	68
October 4, 1961	56
January 2, 1962	35

Now we have inspected both monthly and daily Jupiter activity plots. The monthly plots cover up the day-to-day variations, whereas the daily plots exhibit a good deal of bumpiness. Perhaps it would be worthwhile to examine a degree of smoothing between these extremes.

Figure 58 contains 10-day activity plots of the 1961 Florida data at 18 Mc/s, showing the dates the different planets were at zenocentric inferior conjunction. The activity values have been adjusted to correspond to an Earth-Jupiter distance of 5 A.U. The points on the curves are 10-day averages of the daily activity index rates, and each point is plotted at the center of the 10-day period over which the average was taken. In curve (a) the first 10-day period is February 6 - 16. In (b) the first period is February 1 - 11. Notice that in plot (a) the conjunction dates fit the minima of the curve remarkably well. In plot (b), where the periods over which the averages are taken have been shifted five days with respect to the 10-day periods in (a), the correlation of conjunction dates and minima is not as good. The zenocentric inferior conjunction of Venus on June 11 fits a minimum in (a) and a maximum in (b). The earth conjunction seems to fall a little off-center of a general decline in Jovian activity. This assymetry of the decrease in Jupiter's decameter radiation with respect to the position of zenocentric inferior conjunction of the Earth was also mentioned in connection with Figure 55. Notice that in plot (b) of Figure 58 there are several 32-day cycles. There was a suggestion of a single 32-day cycle in the 1957 data (28).

We have been examining zenocentric inferior conjunctions of Mercury, Venus, and Earth; that is, times when Jupiter and one of these planets had the same heliocentric longitude. In searching for the screening effect of a planet's magnetosphere on solar plasma trying to get to Jupiter, where it might stimulate decameter emission, we should

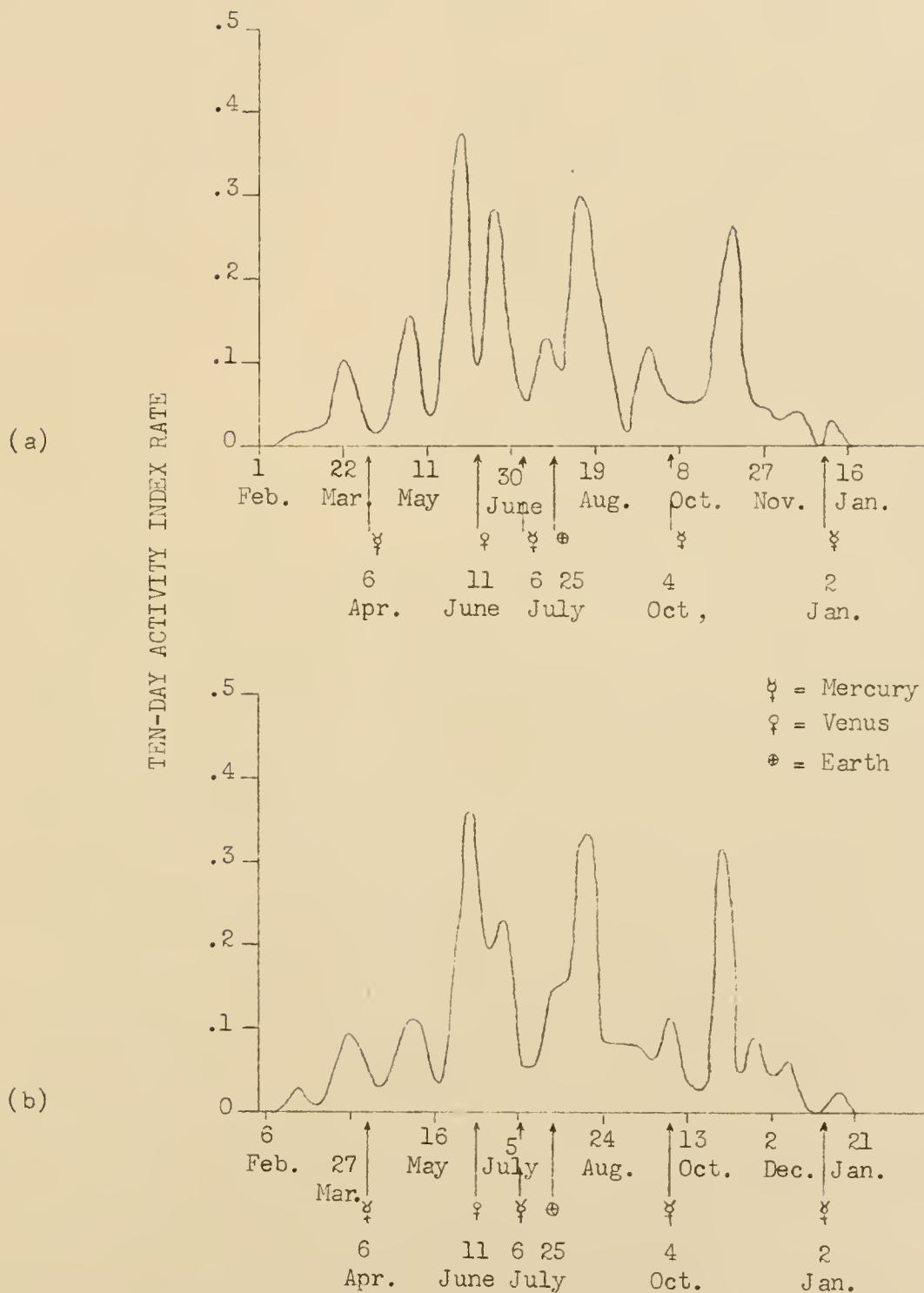


Figure 58.--Ten-day activity plots of the 18 Mc/s Florida data of 1961 showing the dates the planets were at zenocentric inferior conjunctions. The ordinate values represent the average daily activity index rate for a 10-day period and have been adjusted to correspond to an Earth-Jupiter distance of 5 A.U. In (a) the first 10-day average is for the period Feb. 6-16; in (b), Feb. 1-11. Comparison of the two curves shows the effect of the 5-day shift.

also consider the difference in the heliocentric latitudes of Jupiter and the planets. Table 8 contains these data for the zenocentric inferior conjunctions occurring during recent Jupiter apparitions.

TABLE 8

Heliocentric Latitude Differences at
Zenocentric Inferior Conjunctions

Date	Heliocentric latitude of Jupiter	Heliocentric latitude of planet	Difference in heliocentric latitude
1-23-57	+ 1° 15'	Mercury + 5° 43'	4° 28'
1-17-58	+ 1° 17'	Mercury + 3° 16'	1° 59'
3-17-58	+ 1° 16'	Venus + 2° 39'	1° 23'
1-13-59	+ 1° 2'	Mercury - 0° 7'	1° 9'
4-13-59	+ 0° 56'	Mercury - 0° 50'	1° 46'
1-9-60	+ 0° 33'	Mercury - 3° 8'	3° 41'
1-16-60	+ 0° 32'	Mars - 0° 50'	1° 22'
2-23-60	+ 0° 28'	Venus - 0° 10'	0° 38'
4-9-60	+ 0° 23'	Mercury - 4° 0'	4° 23'
7-9-60	+ 0° 13'	Mercury - 4° 48'	5° 1'
4-6-61	- 0° 17'	Mercury - 6° 17'	6° 0'
6-11-61	- 0° 25'	Venus - 2° 15'	1° 50'
7-6-61	- 0° 27'	Mercury - 6° 42'	6° 15'
10-4-61	- 0° 37'	Mercury - 6° 54'	6° 17'
1-2-62	- 0° 46'	Mercury - 7° 0'	6° 14'

If solar plasma was spewed forth from the Sun in its equatorial plane, then the screening effect of a planet's magnetosphere would be most effective at the zenocentric inferior conjunctions when the differences in the heliocentric latitudes of Jupiter and its inferior planets were a minimum.

Assuming that the average velocity of solar plasma is 1×10^3 km./sec., Table 9 lists the lag times for the transit of solar particles.

TABLE 9
Lag Times for the Transit of
Solar Particles

	Sun to planet	Planet to Jupiter
Mercury	.67 day	8.35 days
Venus	1.25 days	7.77 days
Earth	1.73 days	7.29 days
Mars	2.64 days	6.38 days

The 18 Mc/s daily activity index rate plots in Figures 35, 41, 42, 46, and 47 show the dates of zenocentric inferior conjunction of Mercury, Venus, Earth, and Mars. The time lags for the effects of magnetosphere screening to reach Jupiter are indicated by horizontal arrows.

After examining the data presented in this section, the writer draws the following conclusions. Possible deviation of the solar stream by Venus and Mercury is indicated in some cases by a decline in Jupiter decameter activity, but the data are not sufficient to prove the existence of the effect. The evidence in favor of deflection of solar plasma

by the earth's magnetosphere is much more convincing. The monthly activity plots are the best indication, since they smooth out the bunching tendency in the decameter radiation and cover up any short-term cycle effects.

The earth's magnetosphere has been probed by satellites, and a fair idea of its size has been gained. Assuming that the diameter of the magnetosphere in the plane perpendicular to the solar wind direction and containing the axis of rotation of the Earth is 2×10^5 km., then the angular diameter of the eclipsing cross section of the magnetosphere as seen from Jupiter is 0.0182 degree. It is believed that the interplanetary magnetic field strength equals the earth's field strength somewhere between 20 and 35 earth radii (43). If we assume that the terrestrial magnetic field begins effectively to deflect solar plasma away from Jupiter at 35 Earth radii, then computations show that the angular diameter of the eclipsing cross section of the magnetosphere as seen from Jupiter is 0.0406 degree. The angular diameter of the Sun as seen from Jupiter is 0.103 degree. Thus, at opposition, the earth's magnetosphere eclipses roughly 3 to 16 per cent of the area of the solar disk.

The relative angular velocity of the Earth and Jupiter at opposition is 0.132 degree per day. The interval between first and fourth contacts of the earth's magnetosphere with the solar disk is 0.92 to 1.09 days. This duration is much shorter than the length of the period of relatively low Jupiter activity around opposition. Certainly this is one of the weak points in the hypothesis of solar plasma deflection by the earth's magnetosphere. It might be that the earth's magnetic

field exerts its influence well beyond 35 earth radii, although the present space probe data does not support this view. It is also possible that the solar energy storage process at Jupiter has a slow build-up time; whereas the energy decay, feeding the decameter emission process, is rapid. This might account for the prolonged periods of reduced Jovian activity.

In 1960 the geomagnetic index A_p was quite large about eight days preceding opposition. This is an indication that solar plasma was in the vicinity of the earth. Around opposition there was a decline in Jupiter activity. The implication is that the Earth's magnetosphere prevented the solar plasma from arriving at Jupiter. If the solid disk of the earth were blocking out part of the solar stream or if the terrestrial ionosphere were focusing more ultraviolet on Jupiter, the decline in Jovian activity would be imperceptibly small. The fact that the dip in Jupiter activity is noticeable on so many of the monthly activity plots is good evidence that solar plasma may play a fundamental role in the decameter emission process.

CHAPTER III

SOLAR CORRELATION IN 1961 AND COMPARISON WITH PREVIOUS YEARS

Since the sun's influence is evidenced in many terrestrial processes which occur on a planetary scale, such as atmospheric tides, auroral activity, polar cap absorptions, magnetic disturbances, and short wave fadeouts due to enhanced ionization, it is quite reasonable to suspect that the sporadic decameter bursts from Jupiter might be correlated with solar activity. In this chapter we shall search for correlations between the Jovian radio emissions and indices relating to solar activity by examining the data collected by the University of Florida radio astronomy group during the period 1957 - 1961.

Long-Term Inverse Correlation with the Sunspot Cycle

After examining the 1957 - 1960 Jupiter data, the Florida group reported the apparent inverse correlation of the Jovian radiation probability with sunspot number (2). The 1962 apparition of Jupiter has supplied more data which support this observation. Figure 59 is a comparison of the averaged probability of occurrence of decameter radiation at 18 Mc/s and 22.2 Mc/s with the sunspot cycle (45). The averaged probability of occurrence values were obtained by averaging the 72 numbers in the histogram table generated by the computer for each apparition. Each value represents the planet-wide probability of occurrence

for radiation of the given frequency and is plotted as a function of the mean epoch of the apparition. The top curve in Figure 59 is a plot of the "12-month" smoothed Zurich daily sunspot numbers. The inverse correlation of the probability of occurrence of Jovian radiation with the sunspot cycle is evident. Such a trend might imply the existence of a Jovian ionosphere, the increased ionization of which near sunspot maximum would make the escape of radiation from lower levels less probable (46). Warwick has suggested that interplanetary space might be more opaque around sunspot maximum due to the presence of diffusing or scattering clouds of solar plasma (47). Continued monitoring of the decameter signals through the period of sunspot minimum will be necessary to verify the apparent negative correlation between the planet-wide probability of emission and the sunspot cycle.

If the fact that the widths of the peaks on the histograms are considerably less than 180° implies ionospheric focusing, then peak width should vary with the sunspot cycle, because the critical frequency depends on ion density. Figure 60 shows the variation in the width of source A from 1957 to 1961. The sunspot curve is included for comparison. The widths of the peaks were measured at half-maximum height on the smoothed, merged histograms of the 18, 20, 22.2, and 27.6 Mc/s data. All four curves in Figure 60 indicate an inverse correlation of source width with sunspot number. This is interpreted by the writer as evidence supporting the postulation of ionospheric-type focusing. Douglas wrote in 1960, "There is no considerable variation in width of peak in a systematic fashion with the sunspot cycle, although small ($< 10^\circ$)

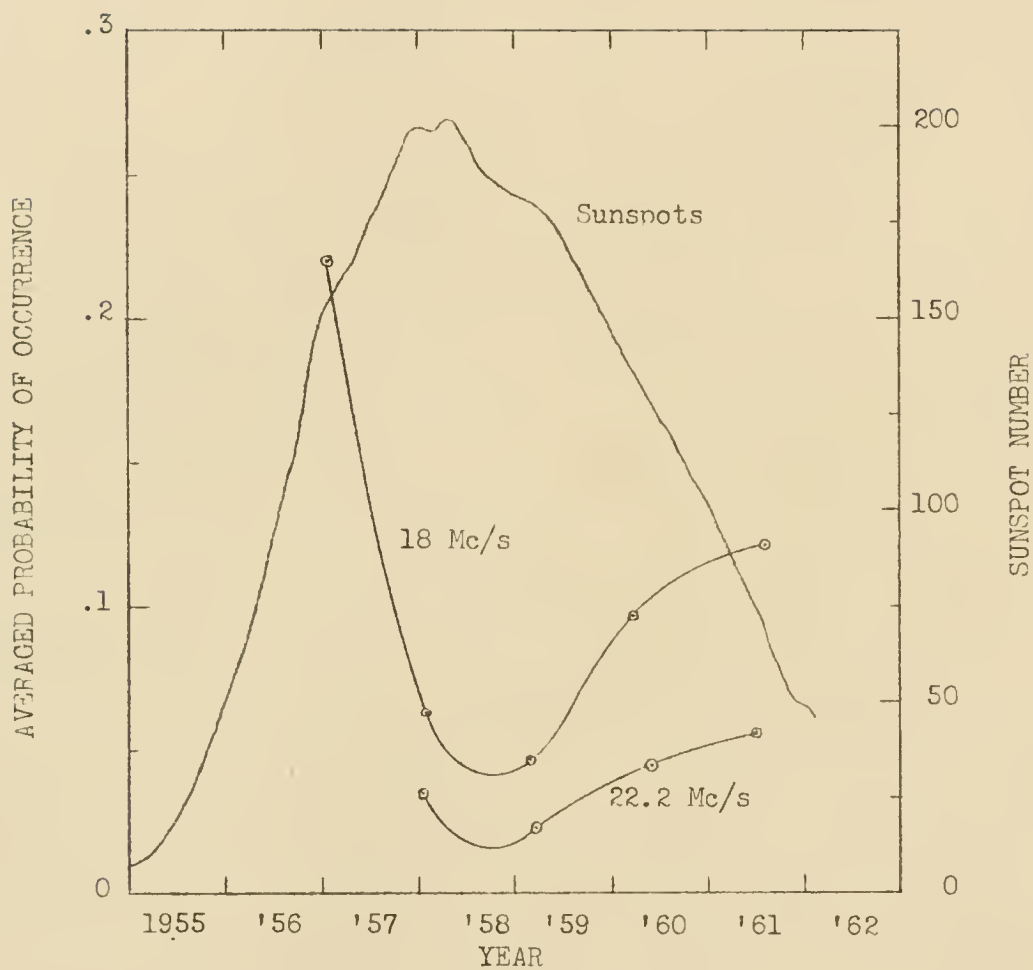


Figure 59.--The long-term inverse correlation of the occurrence of decameter radiation with the sunspot cycle. The 18 Mc/s and 22.2 Mc/s data were collected at the Florida station.

variations cannot be ruled out." The analysis of our data, summarized in Figure 60, clearly contradicts Douglas.

A possible explanation of the inverse correlation evident in Figure 59 is found by examining the orbital position of Jupiter at the mean epoch of several apparitions and the corresponding sub-Jovian latitudes on the solar surface (33). Figure 61 shows the Jupiter-Sun geometry and the sunspot belts. Because the Sun's equator is inclined $7^{\circ} 10'.5$ to the ecliptic, Jupiter, in its orbital journey, faces solar latitudes both north and south of the Sun's equator. Table 10 lists the heliocentric longitude and latitude of Jupiter for the mean epoch of each apparition and the solar latitude of the sub-Jovian point.

TABLE 10

Heliocentric Coordinates of Jupiter

Apparition	Mean epoch	Heliocentric longitude of Jupiter	Heliocentric latitude of Jupiter	Solar latitude of the sub-Jovian point
1951	October 8	10°	$- 1^{\circ} 18'$	3.7° N
1955	December 16	142°	$+ 52'$	4.4° S
1957	February 1	173°	$+ 1^{\circ} 15'$	5.0° S
1958	January 30	201°	$+ 1^{\circ} 17'$	2.8° S
1959	February 26	231°	$+ 59'$	0.8° S
1960	April 15	263°	$+ 22'$	1.1° N
1961	August 2	303°	$- 30'$	3.3° N

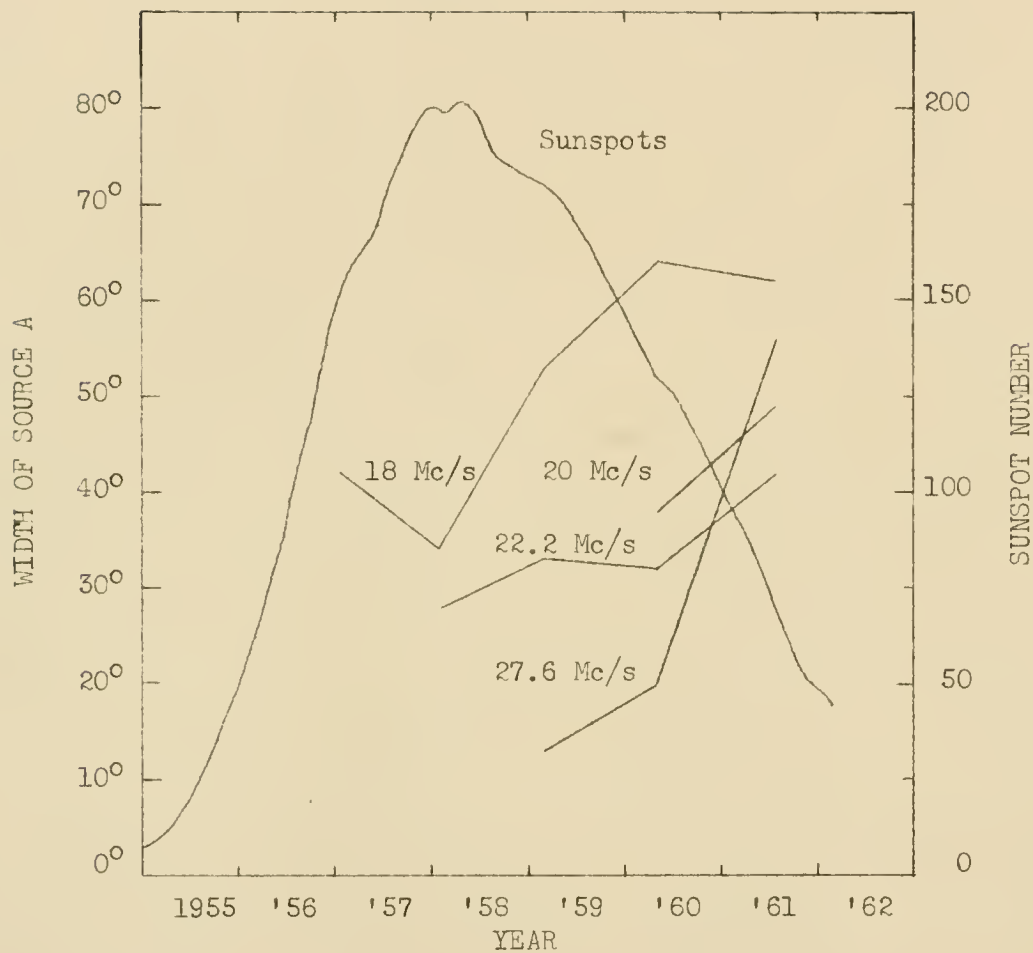


Figure 60.--Comparison of the variation in decameter source width at several frequencies with the sunspot cycle. The measurements of the width of source A were made at one-half the maximum height on the smoothed merged histograms.

In Figure 61, heliocentric longitude is measured eastward along the ecliptic starting at the vernal equinox γ . The longitudes of the ascending and descending nodes of the sun's equator are $73^{\circ} 47'$ and $253^{\circ} 47'$ respectively. In 1951, when Shain made his earliest observations, Jupiter was experiencing maximum exposure to the northern sunspot belt. In 1957 when the Florida group began monitoring the Jovian decameter radiation, the planet was experiencing maximum exposure to the southern sunspot belt. Notice in Figure 59 that at this time the planet-wide probability of emission was a maximum. In 1958 and 1959, when Jupiter faced equatorial latitudes on the solar surface which are usually spotless, Jovian activity was at a low. The probability of emission of radio noise was relatively high in 1961 and again the solar latitude of the sub-Jovian point at the mean epoch of the apparition was approaching the boundary of the northern sunspot belt. A comparison of the apparition activity index rate (defined in the explanation of the Jupiter program for the IBM 709, Chapter II) and the solar latitude of the sub-Jovian point for the five observing seasons 1957 - 1961 is shown in Figure 62. It can be seen that the apparitions of greatest Jovian activity were also the apparitions for which the solar latitudes of the sub-Jovian points were the greatest.

If Jupiter's decameter bursts are stimulated by the ejection of particles from the sun in narrow, vertical beams, then the inverse correlation in Figure 59 might be determined, in part, by the position of the planet relative to the sunspot belts. Caution must be exercised in assuming that this will completely explain the long-term variation of Jovian activity. Although most sunspots occur in the belts, indicated

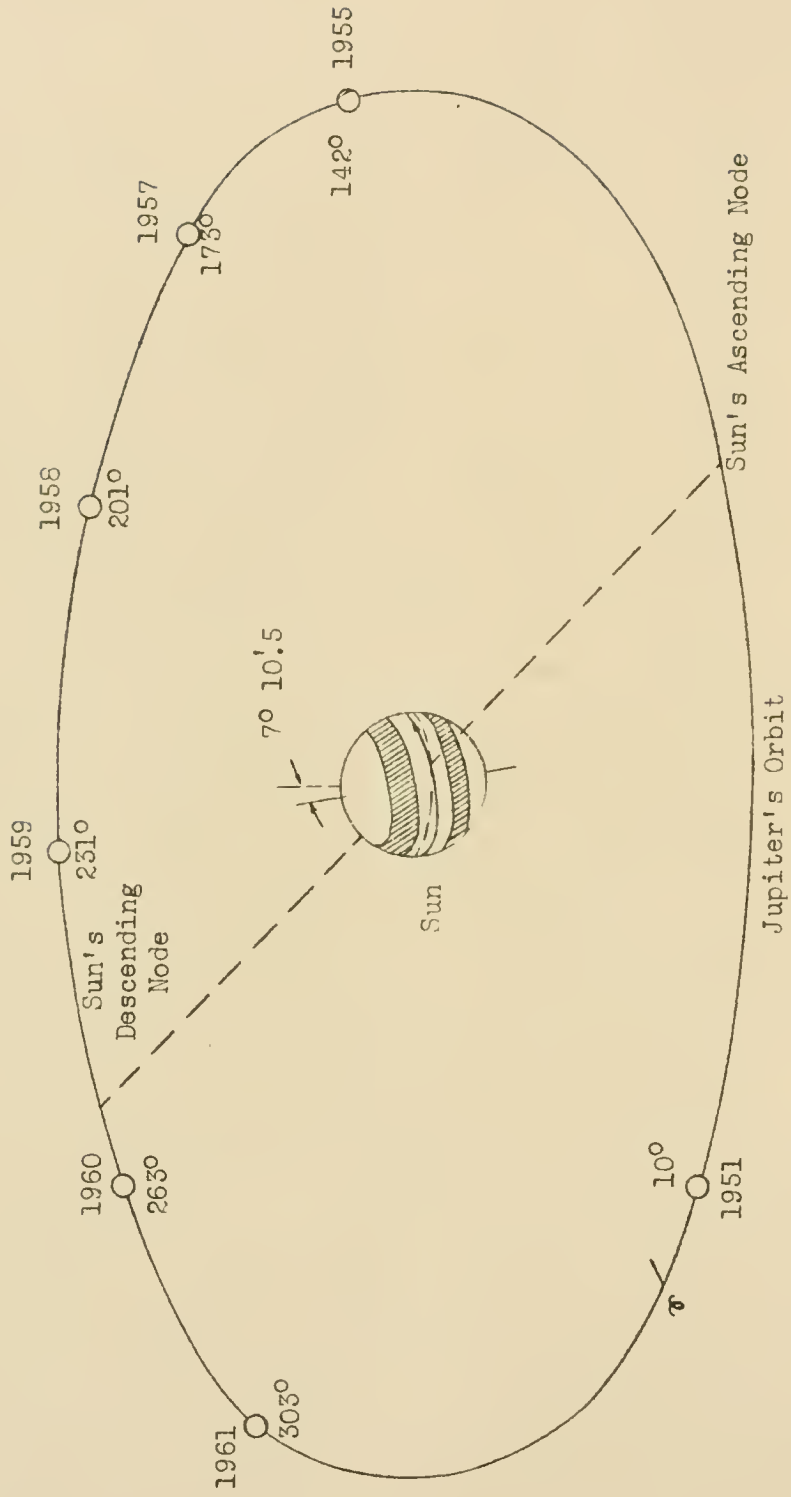


Figure 61.--Jupiter - Sun geometry and the sunspot belts.

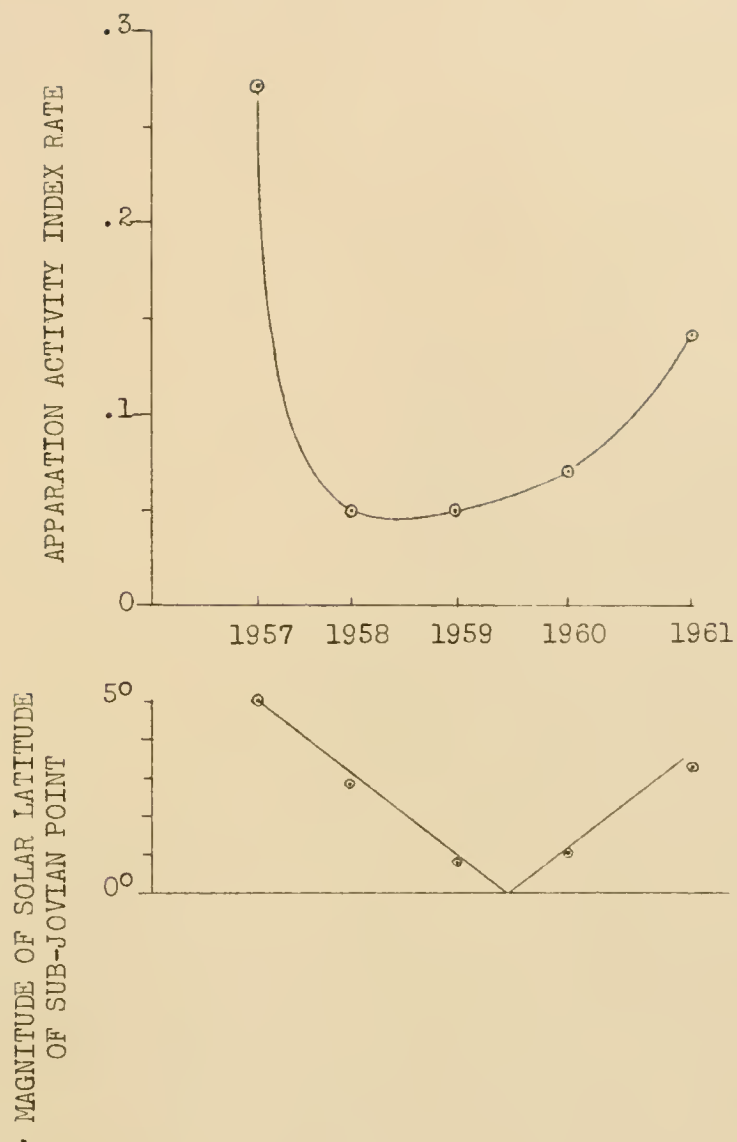


Figure 62.--Apparition activity index rate and magnitude of the solar latitude of the sub-Jovian point plotted as a function of the mean epoch of the observing season.

by shading in Figure 61, between 5° and 30° of north and south solar latitude, some spots occur near the equator at the time of sunspot maximum. Jupiter was in good position to receive particles from equatorial sunspots in 1958 and 1959 during the recent sunspot maximum, yet Jupiter activity was quite low.

T. D. Carr has recently suggested that the 3° tilt of the axis of rotation of Jupiter with respect to the plane of the ecliptic might be a factor influencing the apparent inverse correlation in Figure 59 (48). In 1958, at the time of sunspot minimum, Jupiter was tilted so that its southern hemisphere was facing the Earth. (The celestial longitude of Jupiter's north pole is $9^{\circ} 38' 24''$.) If the northern hemisphere of Jupiter is the active one, it is possible that this maximum tilt away from the Earth in 1958 was the real cause of the decrease in Jovian activity. It is interesting to note that in the optical part of the spectrum the southern hemisphere is more active, hosting the Red Spot, the long-enduring white spots, and the once conspicuous South Tropical Disturbance (19). The separation of these two possible influences on the decameter radiation, i.e., the sunspot cycle and the tilt of Jupiter's axis as seen from Earth, will be difficult because Jupiter's sidereal period is 11.86 years and the average sunspot cycle period is 11.13 years.

In review, the following factors might influence the correlation evident in Figure 59:

1. Increased ionization of a Jovian ionosphere at sunspot maximum due to enhanced ionizing radiations from the sun might prevent the escape of decameter radiation from the lower levels of Jupiter's atmosphere. The evidence presented in Figure 60 supports the Jovian ionosphere postulation.

2. Interplanetary space may become more opaque to the Jovian radiation during sunspot maximum because of the presence of diffusing clouds of solar plasma.
3. If energetic particles ejected from the sunspot zones in narrow vertical beams are responsible for the decameter radiation, then the degree of exposure of Jupiter to the sunspot belts would determine the amount of Jovian activity.
4. Assuming Jupiter's radio noise sources lie in the northern hemisphere, the tilt of the axis of rotation of Jupiter, away from or towards the Earth, might influence the probability of receiving Jovian noise.
5. The increased intensity of the solar wind at the time of sunspot maximum might destroy field-aligned ionic ducts, prohibiting the propagation of decameter radiation out of Jupiter's magnetosphere (48). (The duct theory of propagation will be discussed in Chapter IV.)

Short-Term Correlations

Sunspot Number

There does not appear to be any correlation between sunspot number and Jupiter activity on a daily or monthly scale. The irregular curve on the bottom graph in Figure 63 indicates the variation in sunspot number during the 1961 apparition. Each point is the average Zurich daily sunspot number for a 4-day period. The smooth curve was obtained by three-point averaging. A comparison of this curve with the plot of daily activity index rate, reproduced from Figure 39, reveals no correlation. The approximate 27-day solar rotation period is quite evident on the smooth curve of R_z . There is no 27-day variation noticeable in the daily activity index rate plots in Chapter II.

Figure 64 compares Jupiter's monthly activity index rate during 1961 (taken from Figure 50) with the monthly average sunspot number.

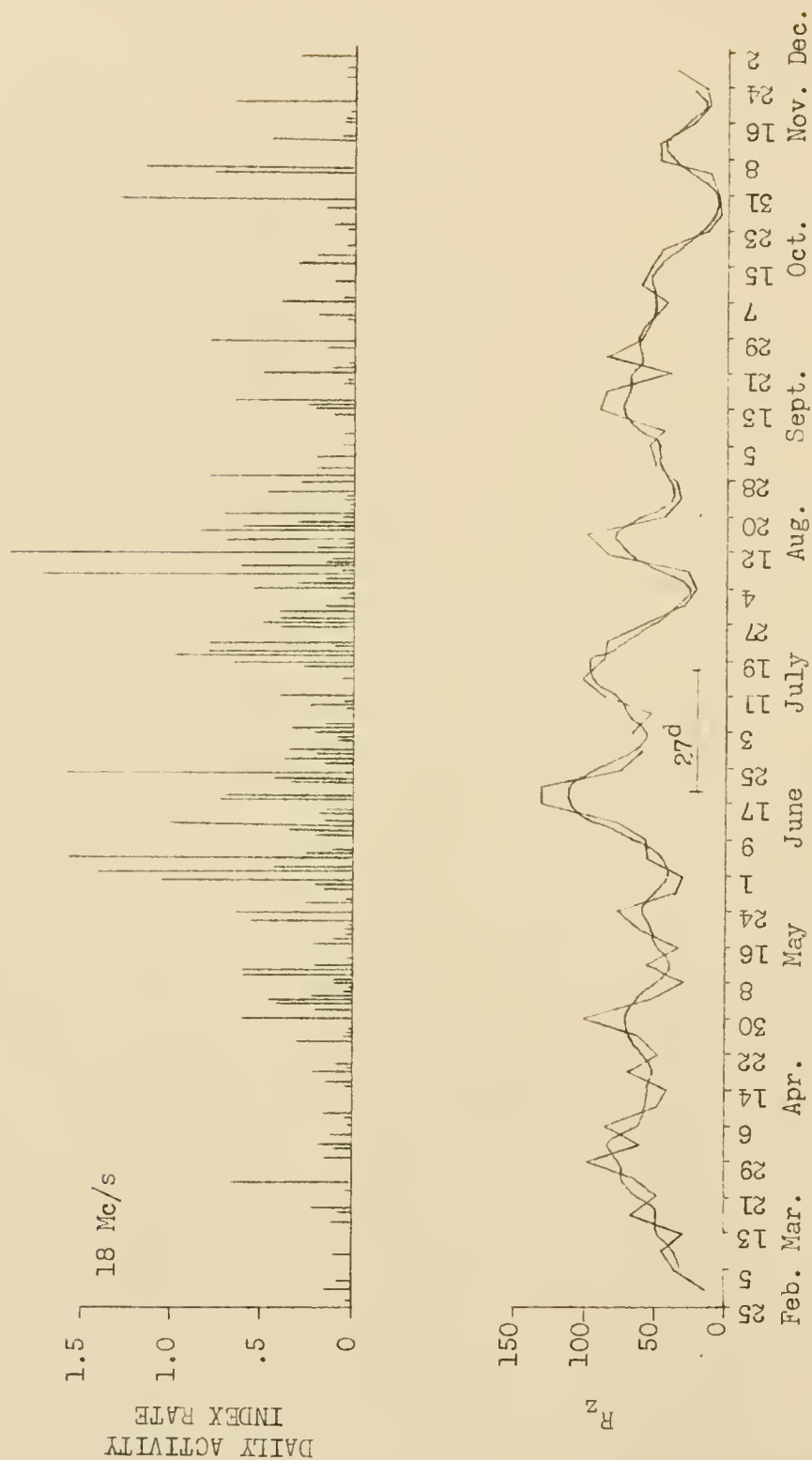


Figure 63.--Daily activity index rate (from Figure 39) and sunspot number variation during the 1961 apparition of Jupiter. Each point on the irregular curve of R_z is the average sunspot number of a 4-day period. The smooth curve was obtained by performing a 3-point running average on the irregular curve.

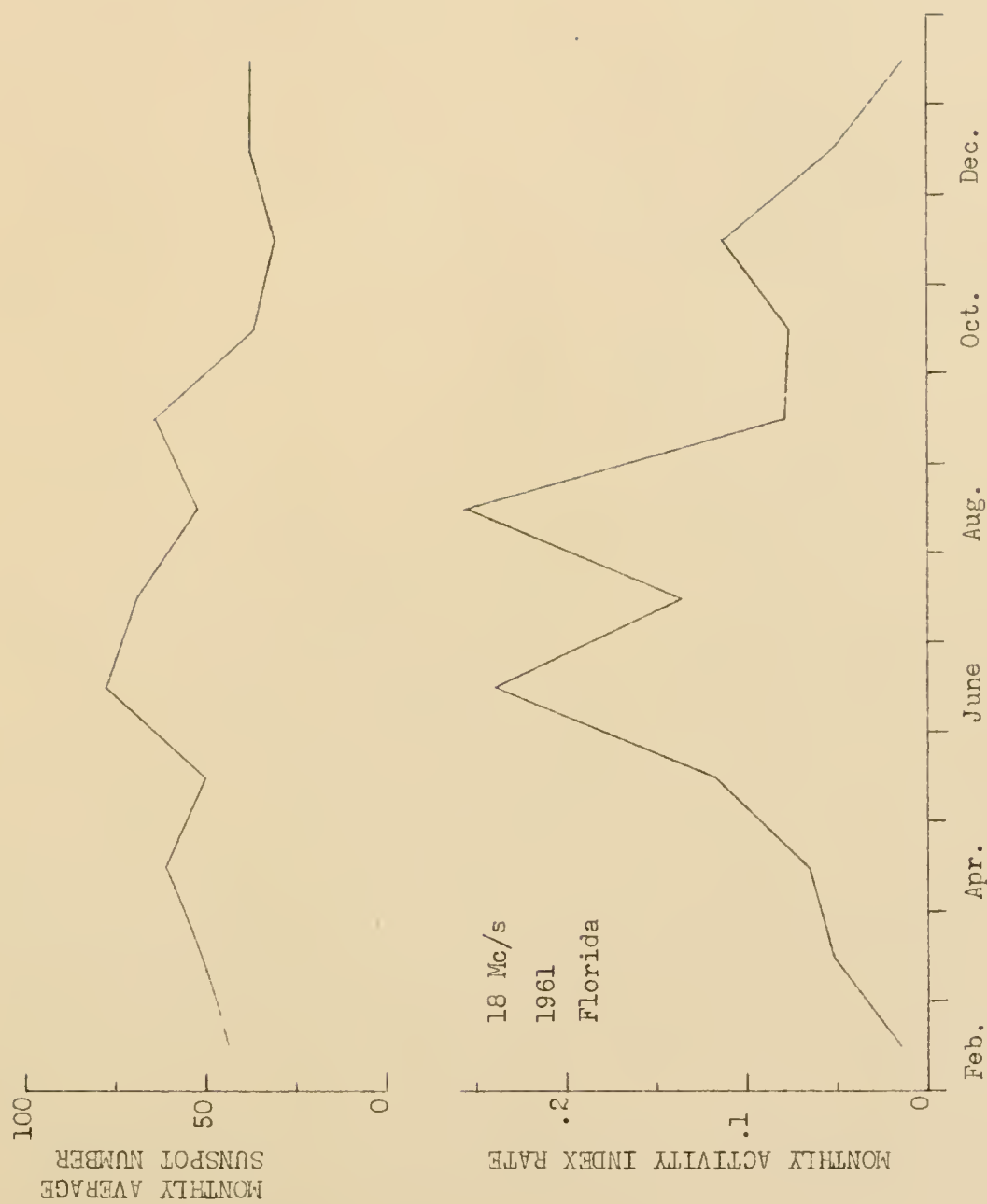


Figure 64.--Monthly average sunspot number and monthly activity index rate for the 1961 apparition.

There is a general rise in the sunspot number curve around opposition, lining up fairly well with the broad maximum of the activity plot; however, it is believed that this is only coincidental. The secondary maxima and minima of the two curves do not line up well at all.

Solar Flare Program for the IBM 709

The solar flare analysis of the Jupiter data was initiated in 1960 (18). Since that time the original IBM 650 computer program has been rewritten for the IBM 709. A brief description of the solar flare program, as it now exists, follows below.

Punched card input-solar flare data. The solar flare program compares the Jupiter activity during an apparition with the solar flare activity during the same apparition. Data concerning each flare which occurred during a Jupiter observing season and was reported in Part B, Solar-Geophysical Data, NBS, Boulder, Colorado, is punched into cards. There is a separate card for each solar flare and the associated information. The following is a list of the data contained on each input card:

- a. date of the flare (month/day/year)
- b. Julian date of the flare
- c. flare period (beginning and end in Universal Time)
- d. solar longitude of the flare
- e. solar latitude of the flare
- f. importance number of the flare
- g. i: the angle between the Sun and Earth as seen from Jupiter
- h. right ascension of the Sun

- i. right ascension of Jupiter
- j. Julian date of Jupiter opposition
- k. A_p , the geomagnetic index

Items a, c, d, e, f, and k are obtained from Part B, Solar-Geophysical Data. Items b, g, h, i, and j are found in The American Ephemeris and Nautical Almanac. The solar latitude and longitude of a flare are measured with reference to the solar equator and the central meridian of the sun as seen from earth. Figure 65 shows the heliographic coordinate system.

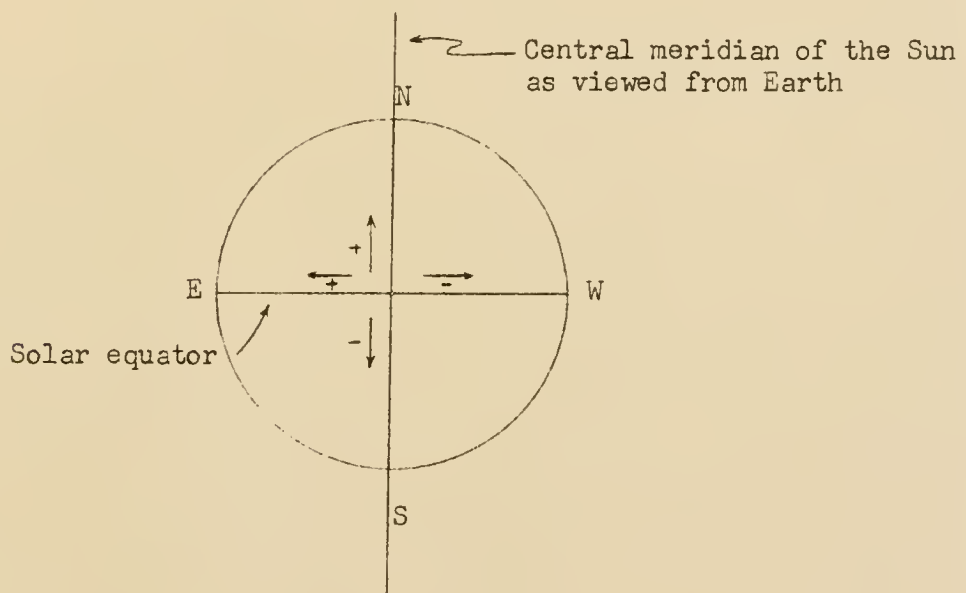


Figure 65.--The heliographic coordinate system.

The latitude of a flare is positive if it is north and negative if it is south of the solar equator. Longitude is positive east and negative west of the central meridian. The importance numbers of the flares range from 1- to 3+, according to the IAU scale. The right

ascensions of the Sun and Jupiter are recorded in hours and minutes. Ap is the daily index of magnetic activity and is an indirect measure of the solar particle-radiation by its magnetic effects. The solar flare program is written so that there must be at least one input card for each day of the Jovian apparition. The days on which no flares were observed are represented by cards punched with zeros.

Tape input from the Jupiter program. During the Jupiter program run on the 709, a magnetic tape is made which stores the following information:

l. Jupiter daily activity index rate

m. daily Zurich relative sunspot number R_z

This tape is used during the solar flare program run.

Punched card input--20 peak days of Jupiter activity. The final information needed before the 709 can begin its computations is the 20 peak days of Jupiter activity during the apparition under analysis. This selection is made by hand, not by machine, from the Jupiter program listing of the daily activity index rate values. The Julian date of each of the 20 peak Jupiter activity days is punched into a card along with the Julian date of the first day of the apparition. These 20 cards, in conjunction with the solar flare data cards and the magnetic tape, comprise the input to the solar flare program. The only restriction in selecting the 20 peak days of Jovian activity is that they cannot be among the first 15 days or the last 4 days of the apparition. The reason for this will become evident upon reading the description of the Chree analysis which follows later in this chapter.

Determination of the flare position with respect to the central meridian of the Sun as seen from Jupiter. The computer performs this computation for each solar flare data card. First, a check is made to see whether the Julian date of the flare precedes or follows the Julian date of Jupiter opposition. On a given date, the angle between the Sun's meridian as viewed from Jupiter and the Sun's meridian as viewed from Earth is found using the relationship:

$$\theta = 15 (\text{RAJ} - \text{RAS}) \pm (i - 180^\circ). \quad [21]$$

RAJ is the right ascension of Jupiter in hours. RAS is the right ascension of the Sun in hours. i is the angle (degrees) between the Earth and Sun as seen from Jupiter. θ is computed in module 360° . The plus sign is used for dates which follow the date of Jupiter opposition, the minus sign for dates preceding the date of opposition. Positive values of θ are measured westward from the sun's meridian as seen from the earth. Negative values of θ are measured eastward.

During the period preceding opposition, the Sun's meridian as seen from Earth is approaching the Sun's meridian as seen from Jupiter, and θ is positive. See Figure 66a. After opposition, the Sun's meridian as seen from Earth and the Sun's meridian as seen from Jupiter are moving apart, and θ is negative. See Figure 66b. To simplify the computation of θ in equation [21], the assumption has been made that the Earth and Jupiter move about the Sun in the same plane.

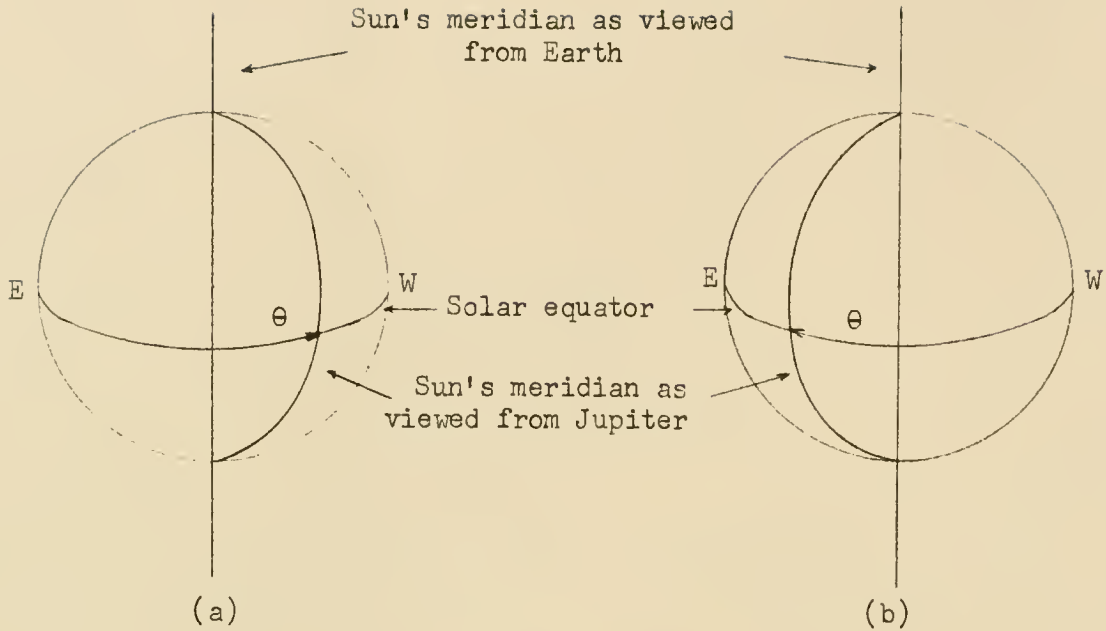


Figure 66.-- θ before and after opposition.

The longitude of a flare with respect to the Sun's meridian as seen from Jupiter, λ_{JM} , is related to the flare longitude with respect to the Sun's meridian as seen from Earth, λ_{EM} , by the equation

$$\lambda_{JM} = \lambda_{EM} + \theta. \quad [22]$$

Since λ_{EM} is input item d and θ has been calculated, the computer can determine λ_{JM} , the flare position with respect to the central meridian of the Sun as seen from Jupiter. To illustrate the geometry and calculations involved, two examples follow.

Example 1.--The determination of the angle between the Sun's meridian as seen from Jupiter and the Sun's meridian as seen from Earth for a date preceding opposition. Diagram (a) in Figure 67 shows the points of intersection of the hour circles through the Sun and Jupiter

with the celestial equator on December 26, 1959. The right ascensions of the Sun and Jupiter are measured eastward along the celestial equator from the vernal equinox γ to the points labelled S and J, respectively, in the diagram. Diagram (b) in Figure 67 shows the planetocentric angle i and the Sun's central meridians as seen from Earth and Jupiter. θ is determined by using equation [21]:

$$\begin{aligned}\theta &= 15 (\text{RAJ} - \text{RAS}) - (i - 180^\circ) \\ &= 15 (17^h - 18^h) - (3^\circ - 180^\circ) \\ &= -15^\circ - (-177^\circ) \\ &= 162^\circ.\end{aligned}$$

The minus sign is used because December 26 precedes the date of the Jupiter opposition occurring during the 1960 apparition. θ is positive and is measured westward from the sun's meridian as seen from the earth.

Example 2.--The determination of the angle θ for a date following opposition. Diagram (a) in Figure 68 shows the points of intersection of the hour circles through the Sun and Jupiter with the celestial equator on August 6, 1960. Diagram (b) shows the geometry involved in the calculation of θ . Again using equation [21], this time with the plus sign since August 6 follows the date of the opposition of Jupiter, one finds that

$$\begin{aligned}\theta &= 15 (\text{RAJ} - \text{RAS}) + (i - 180^\circ) \\ &= 15 (17^h - 9^h) + (8.5^\circ - 180^\circ) \\ &= 120^\circ + (-171.5^\circ) \\ &= -51.5^\circ.\end{aligned}$$

(a)



Right ascension of Jupiter $\approx 17^h$

Right ascension of the Sun $\approx 18^h$

(b)

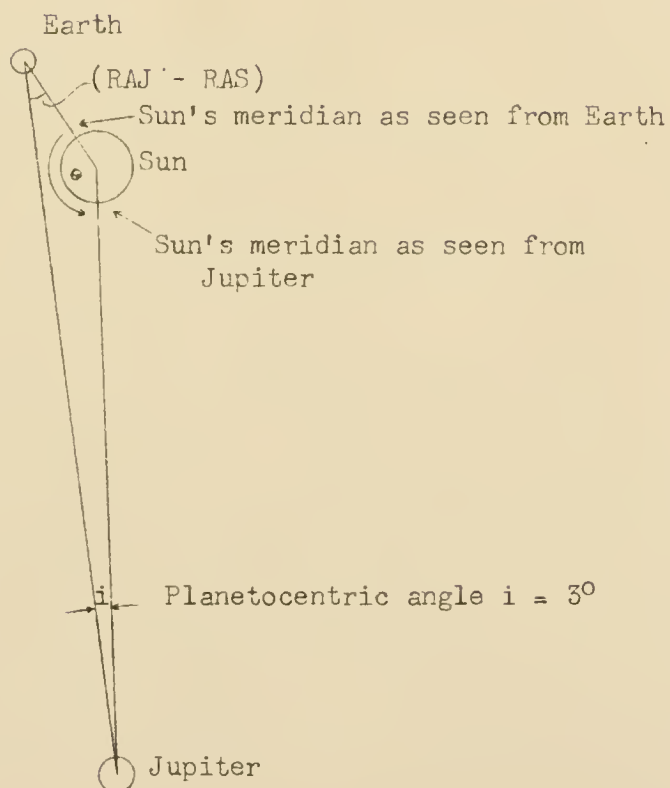


Figure 67.--Geometry involved in the determination of θ (the angle between the Sun's meridian as viewed from Jupiter and the Sun's meridian as viewed from Earth) for December 26, 1959.

(a)



Right ascension of Jupiter $\approx 17^h$

Right ascension of the Sun $\approx 9^h$

(b)

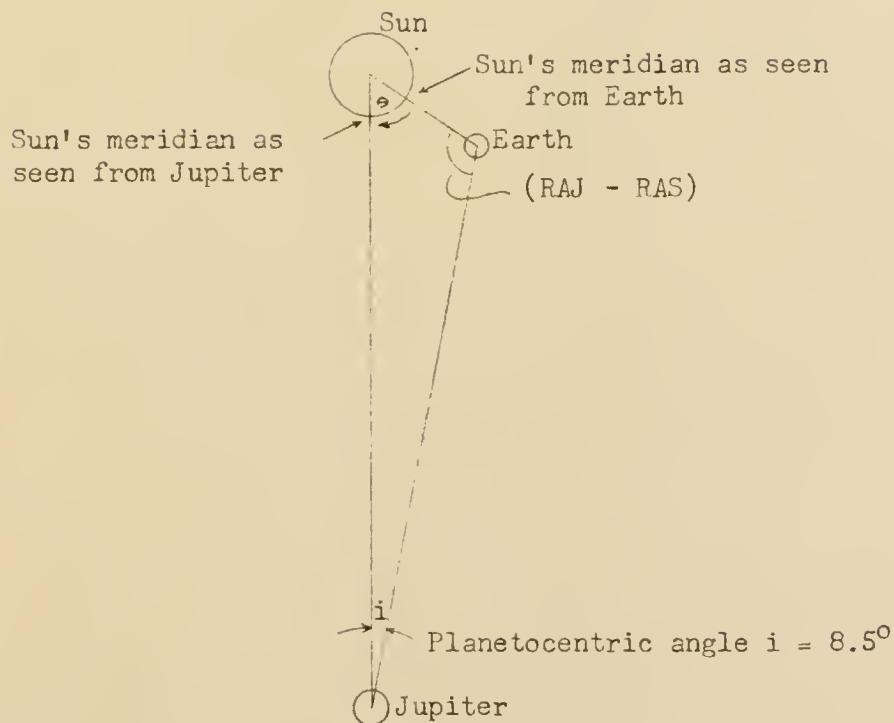


Figure 68.--Geometry involved in the determination of θ (the angle between the Sun's meridian as viewed from Jupiter and the Sun's meridian as viewed from Earth) for August 6, 1960.

θ turns out negative and is measured eastward from the sun's meridian as seen from the earth.

Dividing the flares into three groups according to their location on the solar disk as seen from Jupiter. In order to find out whether flares in the central, western, or eastern portion of the Sun as seen from Jupiter are most effective in stimulating the decameter emission, the program checks the flare location λ_{JM} with respect to the central meridian of the Sun as seen from Jupiter, and assigns the flare to Groups 1, 2, 3, or a combination of groups. Figure 69 shows the regions on the solar disk corresponding to Groups 1, 2, and 3.

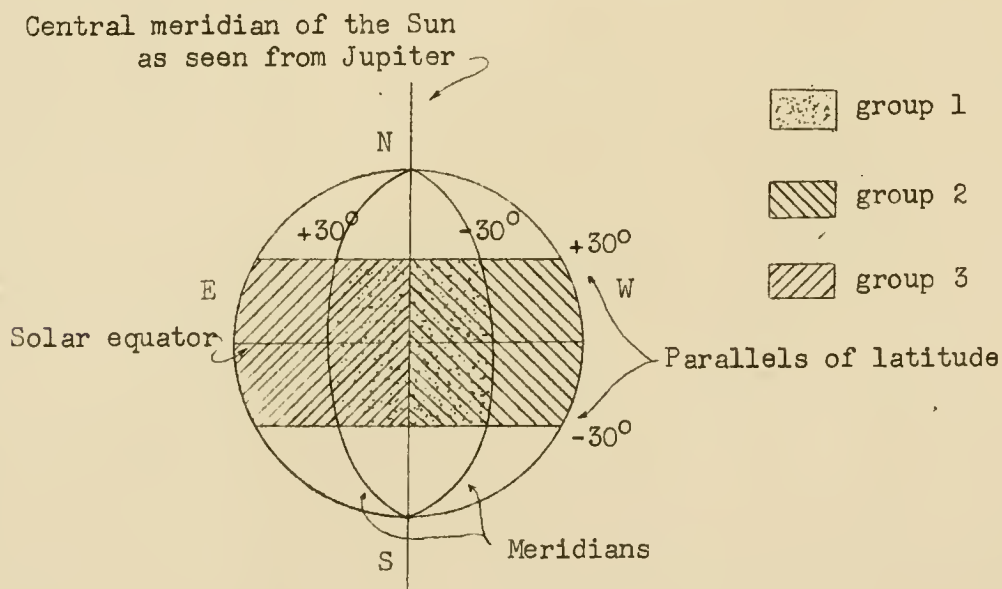


Figure 69.--Regions on the solar disk as viewed from Jupiter determining the designation of flares as belonging to groups 1, 2, or 3.

All three regions are bounded on the north and south by the $+30^\circ$ and -30° parallels of latitude. The program first tests the solar latitude of the flare (input item e).

If $30 - |\text{latitude of solar flare}|$ is

 +, the computer is instructed to proceed to the next test.

 -, the computer is instructed to disregard the flare.

Then the program assigns each flare which lies between the $\pm 30^\circ$ parallels of latitude to a group, to a combination of groups, or to none of the three groups by performing the following tests.

Test for Group 1 (central region)

If $30 - |\lambda_{JM}|$ is

 +, the flare is inside the region.

 -, the flare is outside the region.

Test for Group 2 (0° to 90° west and bounded by the $\pm 30^\circ$ parallels of latitude)

If λ_{JM} is +, the flare is outside the region.

If $90 + \lambda_{JM}$ is

 +, the flare is inside the region.

 -, the flare is outside the region.

Test for Group 3 (0° to 90° east and bounded by the $\pm 30^\circ$ parallels of latitude)

If λ_{JM} is -, the flare is outside the region.

If $90 - \lambda_{JM}$ is

 +, the flare is inside the region.

 -, the flare is outside the region.

Tabulation of daily variables. The computer tabulates the following daily variables.

1. Jupiter daily activity index rate
2. R_z
3. A_p
4. FN1: the number of flares in Group 1 each day
5. FN2: the number of flares in Group 2 each day
6. FN3: the number of flares in Group 3 each day
7. FX1: the flare daily activity index for Group 1
8. FX2: the flare daily activity index for Group 2
9. FX3: the flare daily activity index for Group 3

Items 1 and 2 come directly from the input tape. A_p is input item k. FN1, FN2, and FN3 are the daily totals of the number of flares in Groups 1, 2, and 3. The flare daily activity indices for Groups 1, 2, and 3 are calculated in the following way. The activity index of a single flare is defined by the equation

$$I_f = \beta T. \quad [23]$$

T is the flare duration in minutes and is computed from input item c. β is a constant determined by the importance number of the flare (input item f). Table 11 lists the values of β associated with the solar flare importance numbers. The flare daily activity index for Groups 1, 2, or 3 is found using the relation

$$I = \sum I_f, \quad [24]$$

where the sum is carried over all the flares occurring on a given day in the group under consideration.

TABLE 11

Constants Used in the Determination of the
Activity Index of a Solar Flare

Flare importance number	β
1 -	0.4
1	0.6
1 +	0.8
2 -	0.9
2	1.0
2 +	1.2
3 -	1.5
3	2.0
3 +	3.0

Chree analysis. A statistical method developed by Chree (49) is employed to determine if there is any correlation between the Jupiter daily activity index rate and any of the eight quantities: R_z , A_p , $FN1$, $FN2$, $FN3$, $FX1$, $FX2$, or $FX3$. As mentioned previously, the 20 peak days of Jupiter activity for the apparition under investigation are selected from the Jupiter program listing of the daily activity index rate, and this information is fed to the computer on punched cards. Selecting values from the tabulated daily variables, the computer constructs nine tables, one for each of the variables: Jupiter daily activity index rate, R_z , A_p , $FN1$, $FN2$, $FN3$, $FX1$, $FX2$, and $FX3$.

Table 12 shows the method of construction.

TABLE 12

Chree Analysis Table

Day number in relation to the peak Jupiter activity day		-15	-14	-13	-12	-11	-10	-9	-8	-7	-6	-5	-4	-3	-2	-1	0	1	2	3	4
20 peak Jupiter activity days	1																				
	2																				
	3																				
	.																				
	.																				
	.																				
	19																				
	20																				
Column averages:																					

In the column headed 0, the values of the variable under inspection are listed for the selected 20 peak days of Jupiter activity. In the column headed -1, the values of the variable on the day preceding each peak day or "0-day" are listed. This process is carried on until the table is filled with values of the variable from the 15th day preceding through the 4th day following each selected peak day. The column averages are then computed. These show how the variable under inspection behaves, on the average, during the period from 15 days before to 4 days after strong Jupiter emission. Days on which no Jupiter radiation was received because of equipment failures or poor listening conditions must be guarded against, since they will throw the correlation off.

Output of the solar flare program. The printed output of the 709 solar flare program is a listing of the following quantities for each day of the apparition: FX1, FX2, FX3, FN1, FN2, FN3, R_z , Jupiter daily activity index rate, and Ap, along with the column averages of these nine quantities from the Chree analysis.

Results of the Chree Analysis of the 1961 and 1960 Data

The Chree analysis should reveal any short term correlation existing between Jovian activity and any of the eight daily variables: geomagnetic index Ap, sunspot number R_z , activity index of Group 1, 2, or 3 flares, and number of Group 1, 2, or 3 flares. A search for correlations of these eight variables with the 1961 Jupiter data for 18 Mc/s and 27.6 Mc/s and the 18 Mc/s data of 1960 has been made. The selected 20 peak days of Jovian emission at these frequencies are listed in Tables 13 and 14.

Figures 70, 71, and 72 show the results of the Chree analysis of the 18 Mc/s Jupiter data collected in 1961. The upper two graphs in Figure 70 show how R_z and Ap varied on the average during the period extending from 15 days before to 4 days after a day of strong Jovian emission at 18 Mc/s. On the Ap plot the most prominent features are the maxima at the +3, -3, and -8 days and the minima at the 0 and -6 days. The R_z plot shows a dip on the -5 day. Figure 71 shows the results of the analysis of solar flare activity index of Groups 1, 2, and 3 flares with respect to the 20 days of strongest Jovian emission at 18 Mc/s in 1961. FX1 is the activity index of flares occurring on the central portion of the Sun as seen from Jupiter. The lowest graph

TABLE 13

Peak Days of Jupiter Emission during
the 1961 Apparition

18 Mc/s, Florida	27.6 Mc/s, Florida	18 Mc/s, Florida (June, July, August)
April 30	March 25	June 2
May 24	March 30	June 3
May 31	April 18	June 5
June 2	May 4	June 12
June 5	May 18	June 18
June 12	June 5	June 19
June 18	June 12	June 24
June 19	July 11	June 27
June 24	July 17	July 11
July 21	August 19	July 21
July 23	August 21	July 23
August 7	August 28	July 30
August 9	September 27	August 7
August 12	September 28	August 9
August 29	October 30	August 12
September 15	November 6	August 15
September 28	November 13	August 17
October 30	November 19	August 18
November 5	November 28	August 21
November 21	December 13	August 29

TABLE 14

Peak Days of Jupiter Emission during
the 1960 Apparition

18 Mc/s, Chile	18 Mc/s, Chile (May, June, July)
March 24	May 2
March 29	May 4
March 30	May 6
April 5	May 8
April 17	May 14
April 24	May 16
May 2	May 21
May 6	May 25
May 8	June 1
May 14	June 8
May 21	June 9
May 25	June 11
June 8	June 15
June 9	June 24
June 15	July 8
July 15	July 15
July 23	July 23
July 25	July 25
July 26	July 26
July 27	July 27

in Figure 71 shows a general null from -6 to -12 days. The FX2 plot, which refers to the western portion of the sun, is quite irregular, but does show a broad peak centered at the -11 day. The graph of FX3, referring to the eastern portion of the sun, reveals maxima at the +1, -2, and -12 days and a null from the -7 to -11 days. Figure 72 contains the solar flare number results for Groups 1, 2, and 3 flares. FN1 (flare number on the central portion of the sun) shows a maximum at the +2 day and a minimum from -6 to -10 days. The FN2 plot (flare number on the west side of the sun) has peaks at the +2, -11, and -13 days and a general minimum from -1 to -8 days. The graph of FN3 (flare number on the east side of the sun) shows a slight maximum at the +1 day and a null from -7 to -14 days.

Figures 73, 74, and 75 are the Chree analysis results using the 20 days of strongest Jupiter emission at 27.6 Mc/s during the 1961 apparition. The low ordinate values on the bottom graph in Figure 73 indicate the reduced activity of Jupiter at this higher frequency. The Ap plot shows three broad maxima centered at the +3, -3, and -11 days and minima at 0, -5 to -7, and -13. The top graph in Figure 73 shows no significant variation in R_z around the day of strongest 27.6 Mc/s emission. Figure 74 contains the flare activity index results for Groups 1, 2, and 3 flares. FX1 has a broad maximum from +2 to -3 and a general null from -6 to -13. FX2 is quite irregular with local maxima at +3, +1, and -2 to -7, and local minima at -1 and -8. The plot of FX3 shows two prominent peaks on the -1 and -11 days. Figure 75 contains the flare number results of the search for correlations with 27.6 Mc/s Jovian noise in 1961. FN1 shows practically no variation. FN2 shows a slight

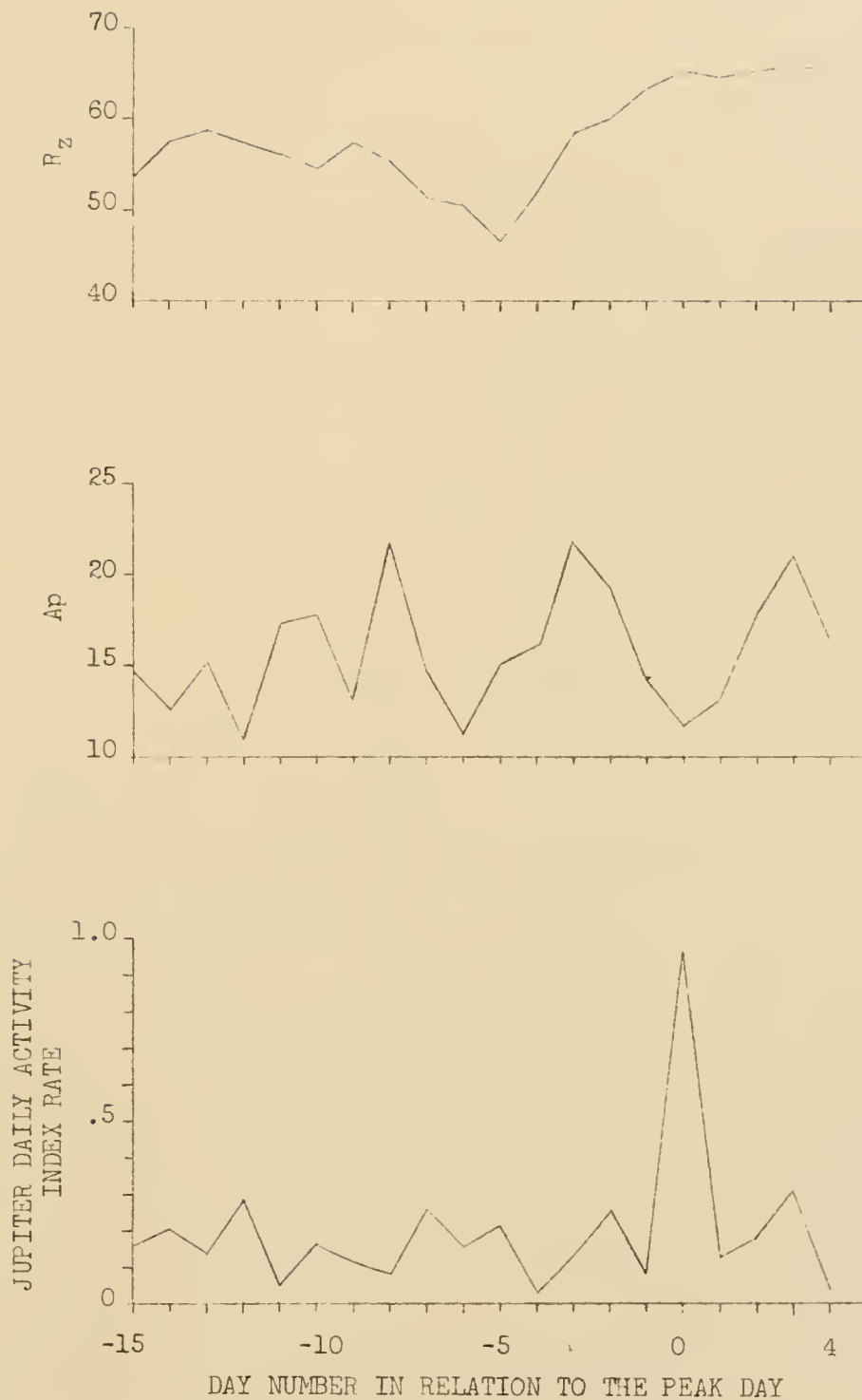


Figure 70.--Chree analysis of Jupiter activity, geomagnetic index A_p , and sunspot number R_z , using the 20 peak days of 18 Mc/s Jupiter emission monitored at the Florida station in 1961.

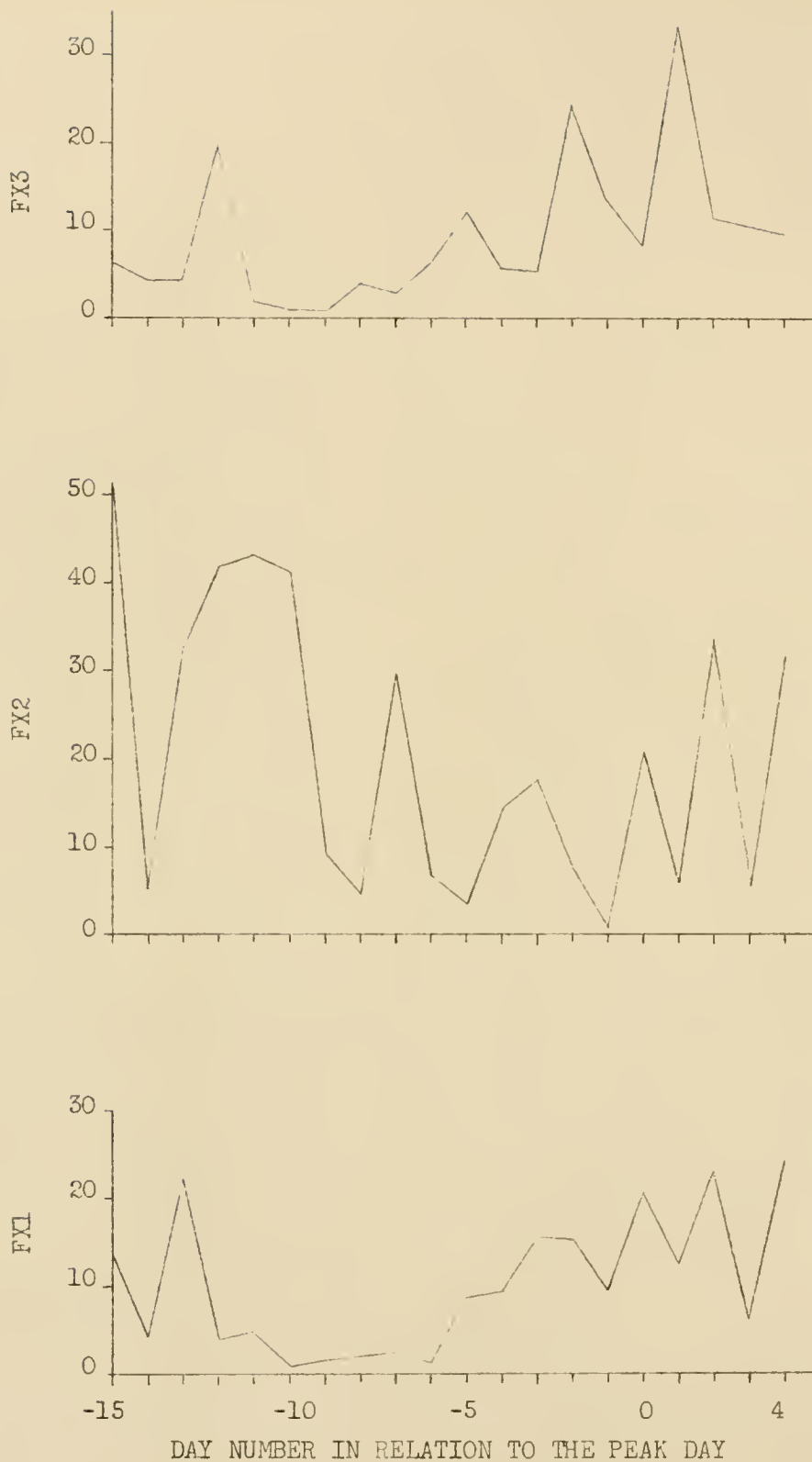


Figure 71.--Chree analysis of solar flare activity index in groups 1, 2, and 3, using the 20 peak days of 18 Mc/s Jupiter emission monitored at the Florida station in 1961.

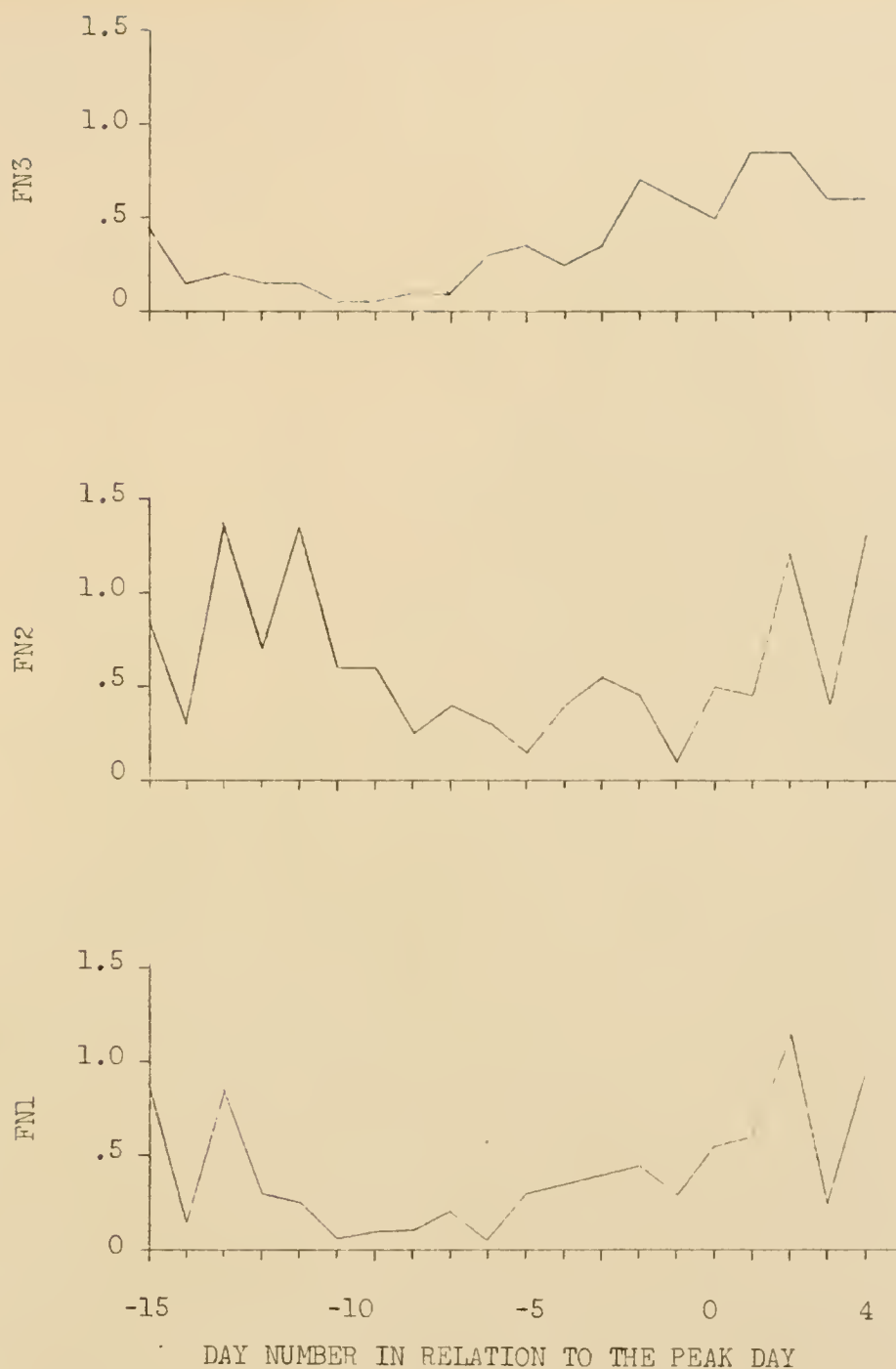


Figure 72.--Chree analysis of solar flare number in groups 1, 2, and 3, using the 20 peak days of 18 Mc/s emission monitored at the Florida station in 1961.

peak at -3 and a minimum from -6 to -8. The graph of FN3 is almost flat.

If energetic particles ejected from the Sun in relatively narrow beams are responsible, directly or indirectly, for the decameter radiation from Jupiter, then around opposition these particles should produce geomagnetic events upon bombardment of the upper atmosphere of the Earth. A few days later, depending upon the velocities of the particles, one would expect an increase in Jupiter activity occasioned by the arrival at the giant planet of this rectilinearly propagated solar plasma. In order to verify this hypothesis, a Chree analysis has been performed, selecting the 20 peak days of Jovian emission from the 3-month period around opposition in 1961. Figure 76 shows the results. As mentioned earlier, A_p is a daily index of the disturbed condition of the geomagnetic field, presumably due to solar plasma bombardment. The most prominent feature of the A_p plot is the null centered on the 0-day and bounded by the maxima at +3 and -3. An interpretation of this result will be given later after examination of a similar correlation in the 1960 data.

Figures 77, 78, and 79 contain the results of a Chree analysis of the 1960 data using the 20 peak days of Jovian radiation at 18 Mc/s. The A_p plot in Figure 77 shows maxima at +2, -8, and -14 and a general null from -1 to -3. The graph of R_z is relatively flat. Figure 78 contains the flare activity index results. There is a slight dip in FX1 from -7 to -12 days. The FX2 plot shows maxima at -4 and -15 and minima at +2 and -10. FX3 has a peak at -10 and a general null from -2 to -5. Figure 79 contains the flare number results. There is not

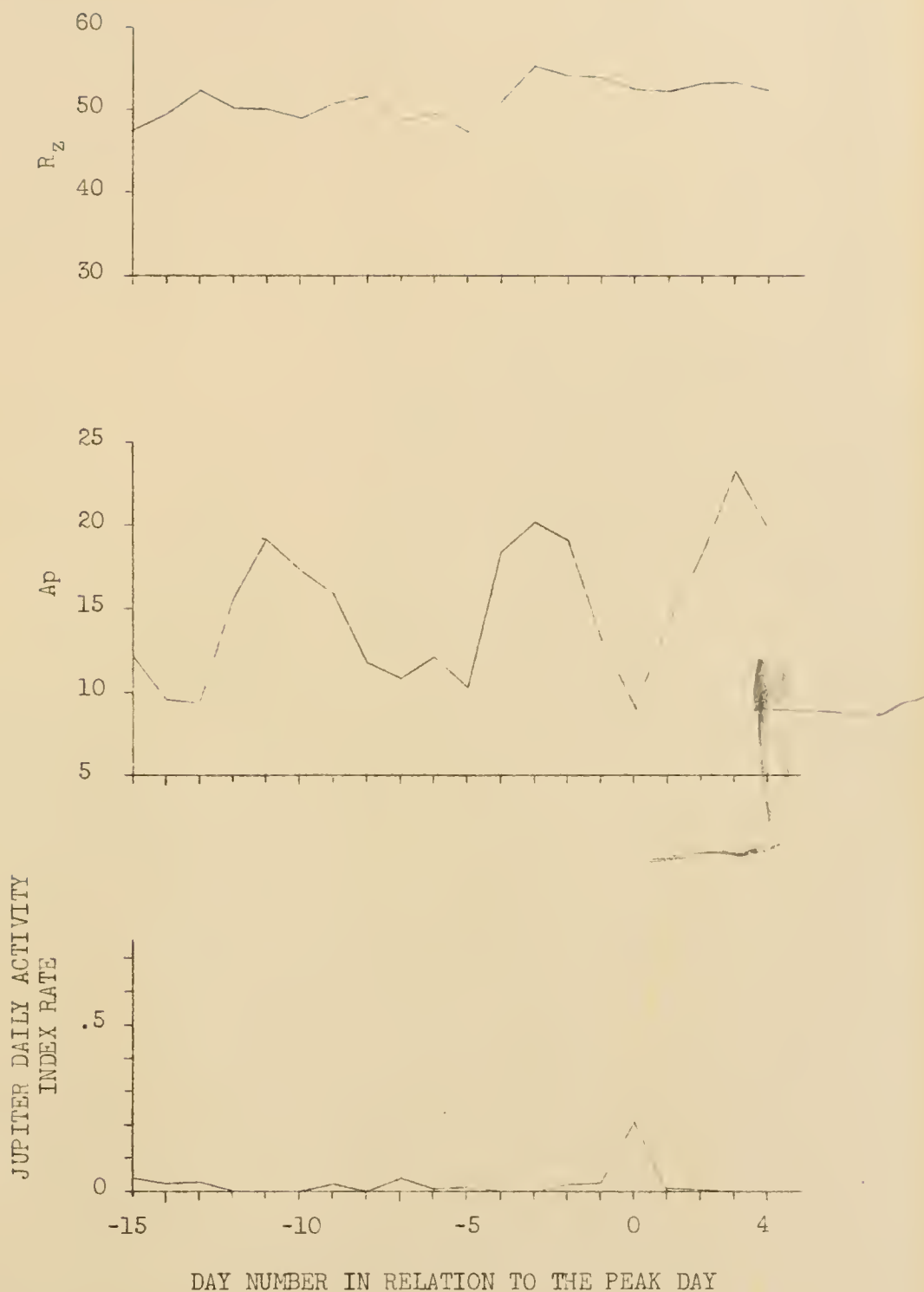


Figure 73.--Chree analysis of Jupiter activity, geomagnetic index A_p , and sunspot number R_z , using the 20 peak days of 27.6 Mc/s Jupiter emission monitored at the Florida station in 1961.



Figure 74.--Chree analysis of solar flare activity index in groups 1, 2, and 3, using the 20 peak days of 27.6 Mc/s Jupiter emission monitored at the Florida station in 1961.

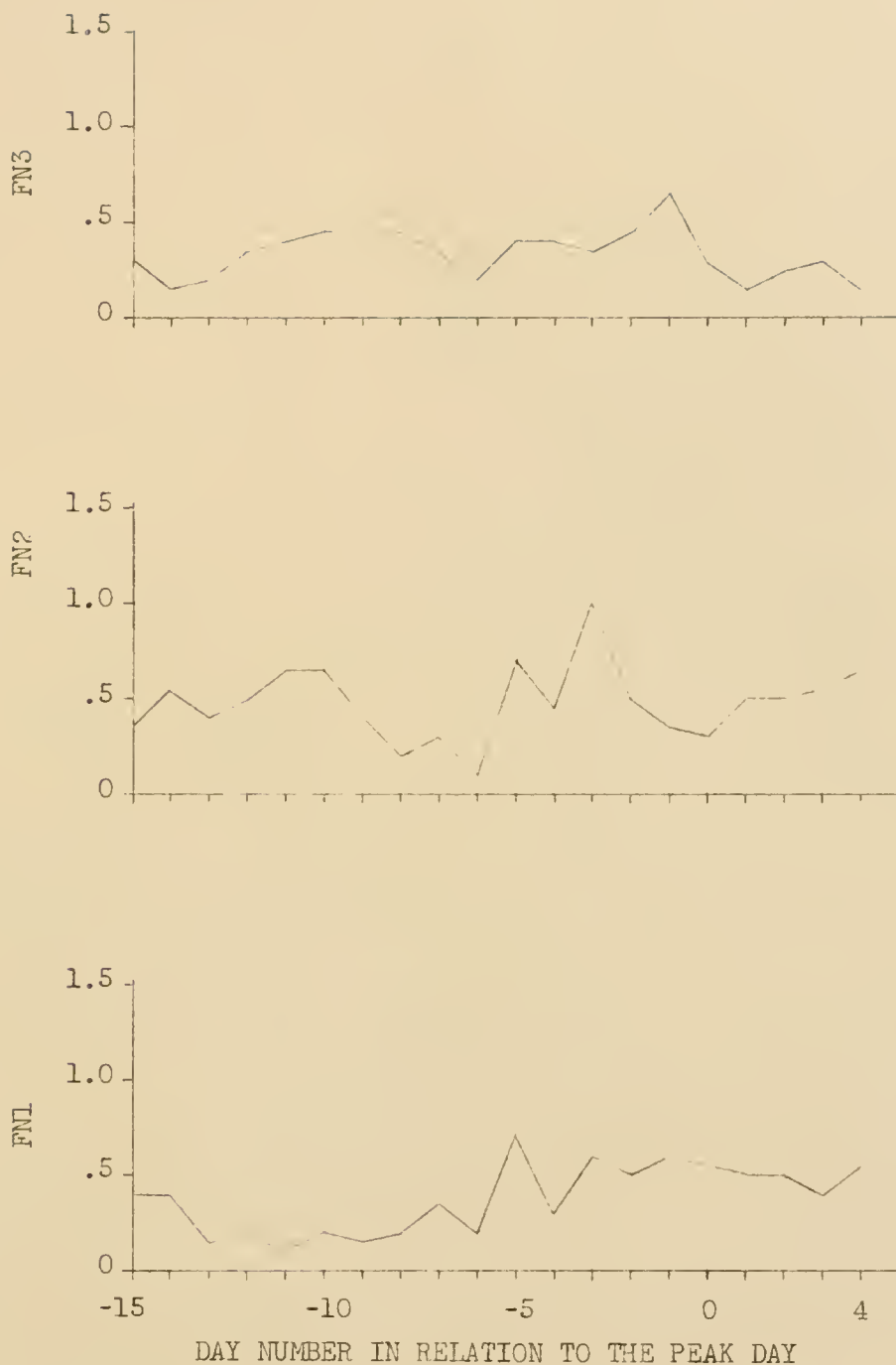


Figure 75.--Chree analysis of solar flare number in groups 1, 2, and 3, using the 20 peak days of 27.6 Mc/s Jupiter emission monitored at the Florida station in 1961.

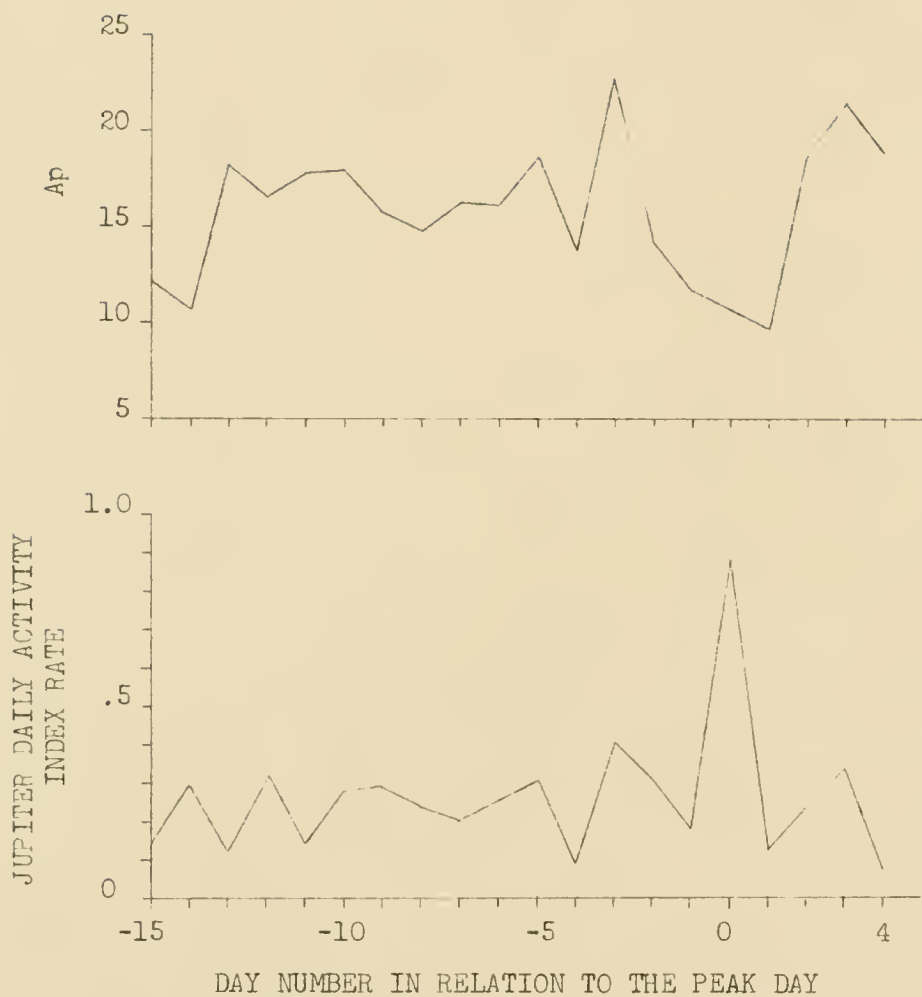


Figure 76.--Chree analysis of Jupiter activity and geomagnetic index Ap using the 20 peak days of 18 Mc/s Jupiter emission monitored at the Florida station during the 3 months around opposition in 1961.

much variation in FN1, except perhaps a general null from -12 to -7. FN2 shows peaks at +4, -4, and -15 and a dip at -10. The plot of FN3 is relatively flat.

Figure 80 shows the results of the analysis of the average variation in the geomagnetic index around a day of strong 18 Mc/s Jovian emission, where the 20 peak days of decameter activity were selected from the 3-month period around opposition in 1960. Notice the prominent maximum in Ap on the -8 day. This same result was obtained by the Florida group using a different technique of analysis in 1960 (50). The plot of Ap also reveals a minimum at -12 and a general null centered on the 0-day.

In summary, the graphs obtained from the Chree analysis of the 1961 and 1960 data have certain features in common which will now be commented upon. The search for correlations between Jupiter activity and Ap during the 3-month periods around opposition has revealed an increase in Ap on the eighth day preceding strong Jovian emission in 1960 and a lesser increase in Ap on the third day preceding strong Jovian emission in 1961. All five Chree analyses of the variation in Ap show a general null around the 0-day. The R_z plots have few traits in common. All three Chree analyses of FX1 exhibit a null from about -12 to -7 days. Plourde found a similar dip from -7 to -9 days in his analysis of the 1957 through 1959 data (18). He also noticed a maximum in FX1 from the -2 to -5 days using the same data and selecting the 20 peak days of Jovian emission from 18 Mc/s records. The results of the 1960 - 1961 analysis fail to show this peak. The FX2 plots have no outstanding features in common. The 1961 graphs of FX3 show a maximum



Figure 77.--Chree analysis of Jupiter activity, geomagnetic index A_p , and sunspot number R_z , using the 20 peak days of 18 Mc/s Jupiter emission monitored at the Chile station in 1960.

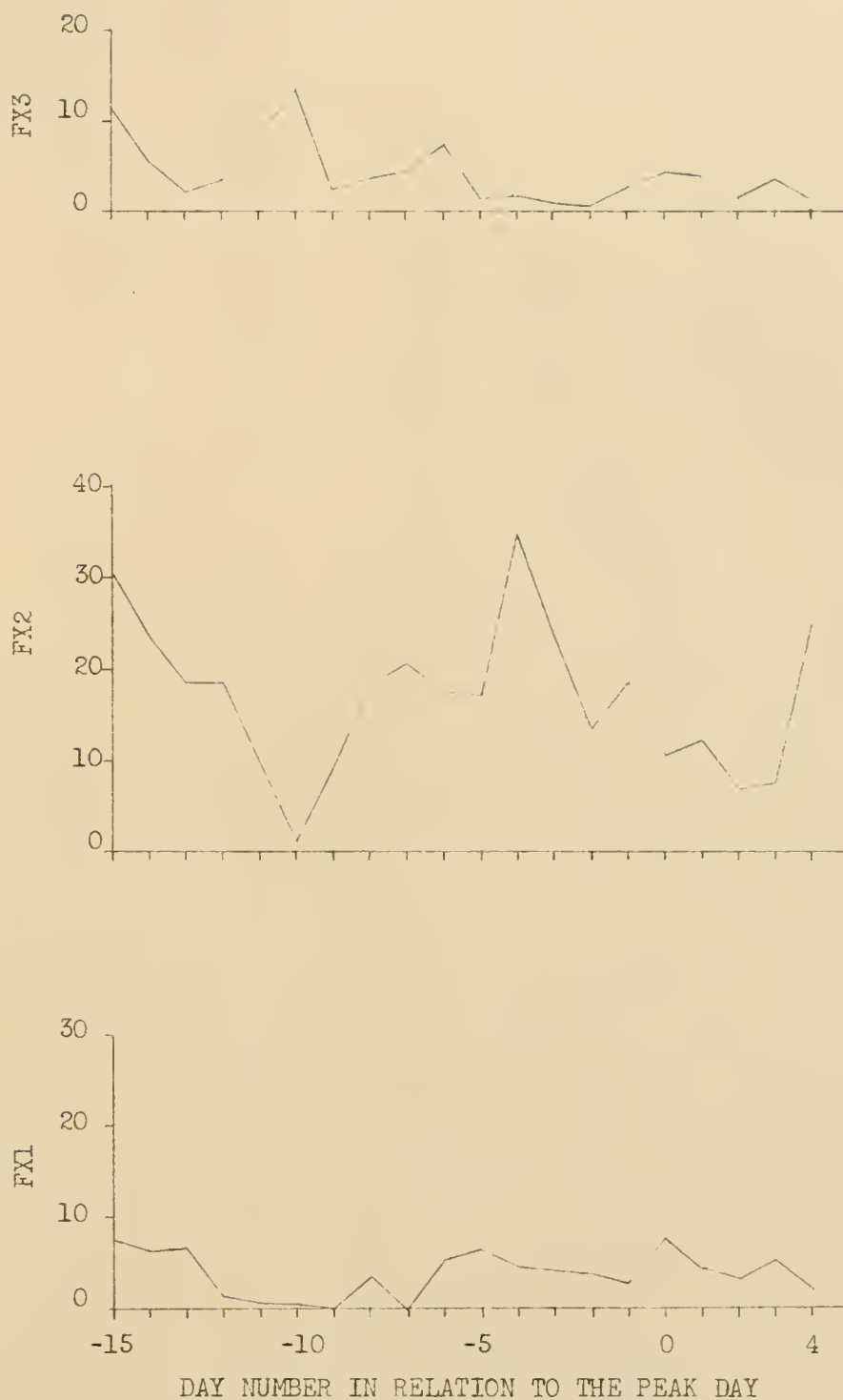


Figure 78.--Chree analysis of solar flare activity index in groups 1, 2, and 3, using the 20 peak days of 18 Mc/s Jupiter emission monitored at the Chile station in 1960.

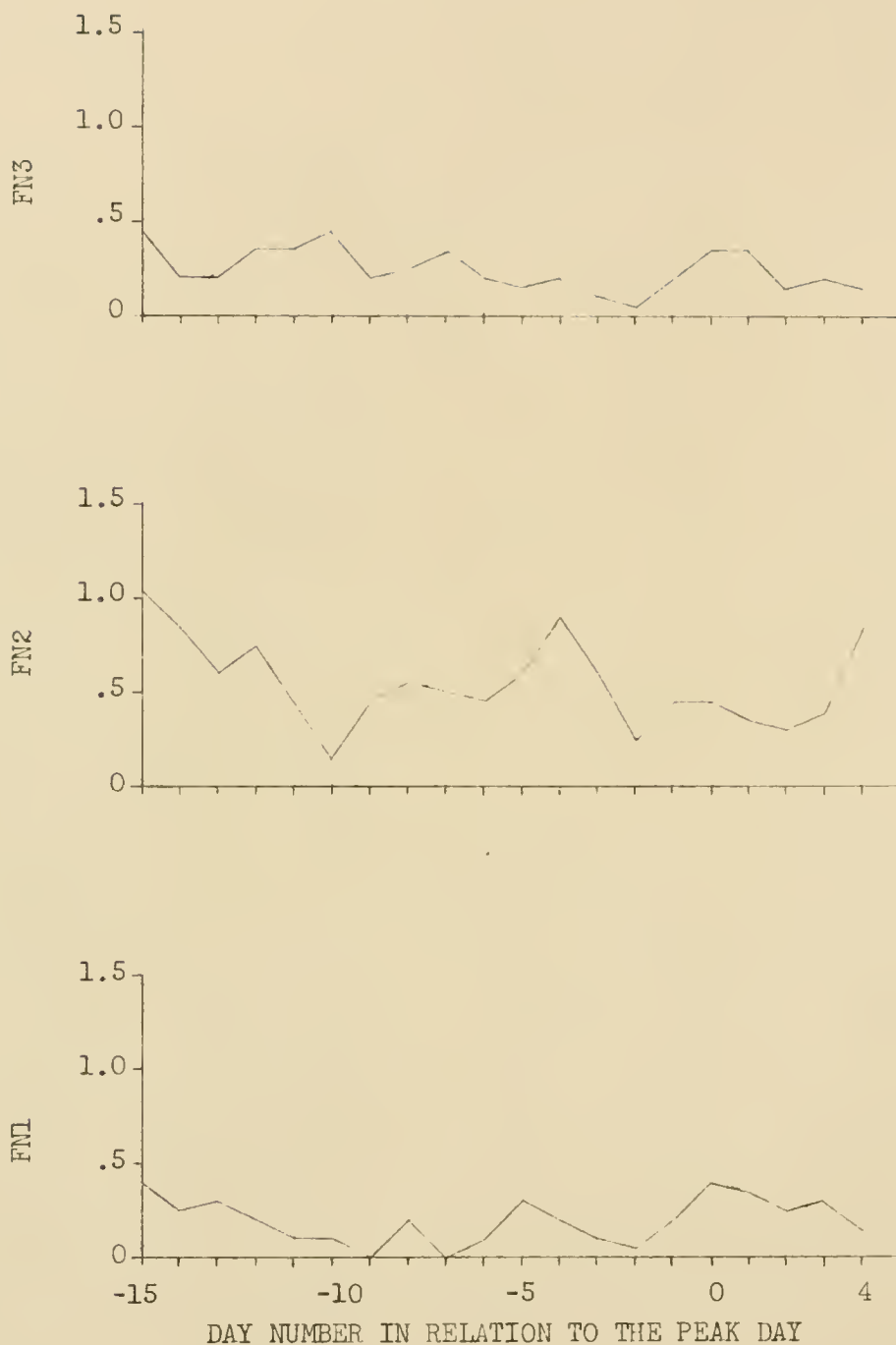


Figure 79.--Chree analysis of solar flare number in groups 1, 2, and 3, using the 20 peak days of 18 Mc/s Jupiter emission monitored at the Chile station in 1960.



Figure 80.--Chree analysis of Jupiter activity and geomagnetic index Ap using the 20 peak days of 18 Mc/s Jupiter emission monitored at the Chile station during the 3 months around opposition in 1960.

at -12. The closest similarity on the 1960 FX3 plot is a maximum at the -10 day. The three FN1 plots show a general null from -6 to -12, in agreement with the variation in FX1. The three analyses of FN2 show no common features, and the same remark applies to the plots of FN3.

What conclusions can be drawn from the Chree analyses of the 1960 and 1961 data? The maximum in Ap eight days before strong Jovian emission in 1960 has been interpreted as evidence that solar particles are responsible for the decameter radiation. The 8-day delay yields a value of approximately 10^3 km/sec for the velocity of the leading particles in the stream. The Chree analysis of Ap for the 3-month period around opposition in 1961 does not show a maximum at the -8 day. Instead, there is a slight maximum in Ap three days before strong Jovian emission. If this is interpreted as meaning that solar particles ejected from the sun in relatively narrow beams with almost three times the velocity of the 1960 plasma triggered the decameter radiation in 1961, then what has caused such a discrepancy in velocity? If, on the other hand, one assumes that the particle velocities have remained constant, then perhaps a change in the condition of the interplanetary magnetic field has produced the disparity in lag-times. The postulation of a stronger interplanetary field in 1960 leads one to the conclusion that the particles which arrived at Jupiter during that year necessarily followed paths of greater curvature, hence they had longer Sun-Jupiter transit times.

The dip in Ap that appeared in all five Chree analyses on the 0-day or day of strong Jovian emission might imply that a scarcity of

high energy particles (solar cosmic rays) results in a particularly undisturbed condition of the Earth's magnetic field and, at the same time, permits the formation of guiding ducts in Jupiter's magnetosphere leading to the reception on Earth of more decameter radiation.

The Chree analyses of R_z in 1960 and 1961 support the earlier conclusion that there is no short-term correlation of sunspot number with Jupiter activity.

The Chree analyses of the flare activity index and the flare number of Group 1 flares suggest a general null extending from 7 to 12 days before strong Jovian emission. This might be interpreted as follows. A scarcity of particle-producing flares results in an undisturbed state of Jupiter's magnetosphere 7 to 12 days later. This quiescent condition at Jupiter might permit the formation of field-aligned ionic ducts which make possible the transmission of decameter radiation out of the Jovian magnetosphere. This conclusion, however, presents a contradiction, for the Ap analysis suggested that solar particles with a 3-day Earth - Jupiter transit time might be responsible for triggering the decameter radiation in 1960 and 1961. The FXI and FNI analyses results suggest that particles with 7-to 12-day Sun - Jupiter transit times are responsible. Although the evidence in favor of the longer transit times is not as convincing as the Ap correlation, one must necessarily conclude that the data analyzed are not sufficient to resolve this apparent dilemma.

The Chree analyses of solar flares in Groups 2 and 3, with the intention of discovering whether flares on the west or east side of the Sun as viewed from Jupiter have the greater influence on the decameter

emission, did not provide the evidence to answer this question. There is a slight suggestion that flares on the east side of the Sun are followed 10 to 12 days later by Jupiter emission, but the evidence is not conclusive. The writer feels that the search for correlations between flares on different regions of the Sun and Jovian radio noise should be continued, since results might be obtained that would lead to a better understanding of the geometry of ejection of solar plasma and the influence of the interplanetary magnetic field.

Certain improvements in the mechanics of the Chree analysis are thought advisable before the search for correlations between daily variables and the sporadic decameter radiation is continued. Due to the bunching of Jovian radiation, typically resulting in 4 to 5 days of emission followed by a like period of no broadcasting, the selection of the 20 days of strongest activity during an apparition should be made in the following way. The interval between the selected peak days of activity should be at least 20 days, because this is the length of the period of correlation (from -15 to +4 days). This will mean that a Chree analysis of the data of any single apparition will be performed using fewer than 20 peak days. It would also seem advisable to attempt to eliminate the effects caused by the bunching of the Jovian radiation by employing smoothing techniques. Other periodicities in the decameter emission, such as the 8-day cycle mentioned in Chapter II, should also be given consideration. In searching for the effect of a suspected stimulus it is always advisable to control other variables which might influence the process under investigation. In the laboratory this is usually not impossible, but in experiments performed on an interplanetary

scale, the problem is somewhat magnified. To be more specific, the first half of Chapter II is devoted to the examination of the longitude dependence of the decameter radiation, yet there has been no attempt to control this variable while performing the Chree analyses. In the future it would seem advisable to select only watch periods during which source A was near the central meridian of Jupiter as seen from Earth during some part of the watch. This would essentially rule out the possibility that the longitude dependence might destroy the effectiveness of the Chree analysis. As an example, suppose solar plasma capable of triggering decameter radiation arrives at Jupiter when longitude 40° (System III) is pointed toward Earth. If decameter radiation is stimulated, there is a slim chance that it will be detected in the direction of the Earth if the periods of good listening during that night's watch are those when the "no-radiating" longitudes of Jupiter are on the central meridian. The fact that no signals are received in this case at the radio observatory should not be interpreted as evidence that the solar particles did not produce decameter emission. If, however, the stimulus lasts several days, this effect would disappear.

Geomagnetic Activity

In the above section a method developed by Chree has been used to search for correlations between solar related variables and Jupiter activity in the decameter range. In the remainder of the present chapter, the search will be continued by examining daily Jovian activity and solar events. The geomagnetic index A_p is a measure of geomagnetic activity--the magnetic variations at the earth's surface usually attributed to a stream of ionized gas from the sun interacting with the

earth's magnetosphere. From an analysis of the 1960 data, the Florida group reported an apparent correlation at about the time of Jovian opposition between geomagnetic activity and the decameter emission 8 days later (2). The 18 Mc/s daily activity index rate curve of the 1961 data collected in Florida is reproduced in Figure 81 along with a plot of A_p for the period around opposition. The A_p time scale is lined up with that of the daily activity index rate plot. There is no sign of a correlation between Jovian activity and the geomagnetic index 8 days later as was evident in the 1960 data. There is a slight suggestion of a 3- to 4-day lag between A_p and strong Jovian emission, but the evidence is not very convincing.

Immediately under the abscissa of the activity index rate plot in Figure 81 the dates of occurrence of geomagnetic storms are marked. This information was obtained from reference 51. Those storms that were characterized by sudden commencements and those that are believed to have been caused by the central meridian passage of active magnetic regions on the sun are designated by the letters "s" and "m" respectively. The dates on which polar cap absorption events were detected are labelled "pca." For five of the geomagnetic storms occurring near opposition, the solar flares thought to be responsible were observed. Knowing the travel time of the particles from Sun to Earth, it was possible to calculate the time of their arrival at Jupiter, assuming constant speed, rectilinear propagation. Table 15 presents the results. As the right hand column of Table 15 indicates, some degree of Jovian activity was found on all five dates when the solar particles were expected to reach Jupiter. Examination of the activity index rate plots

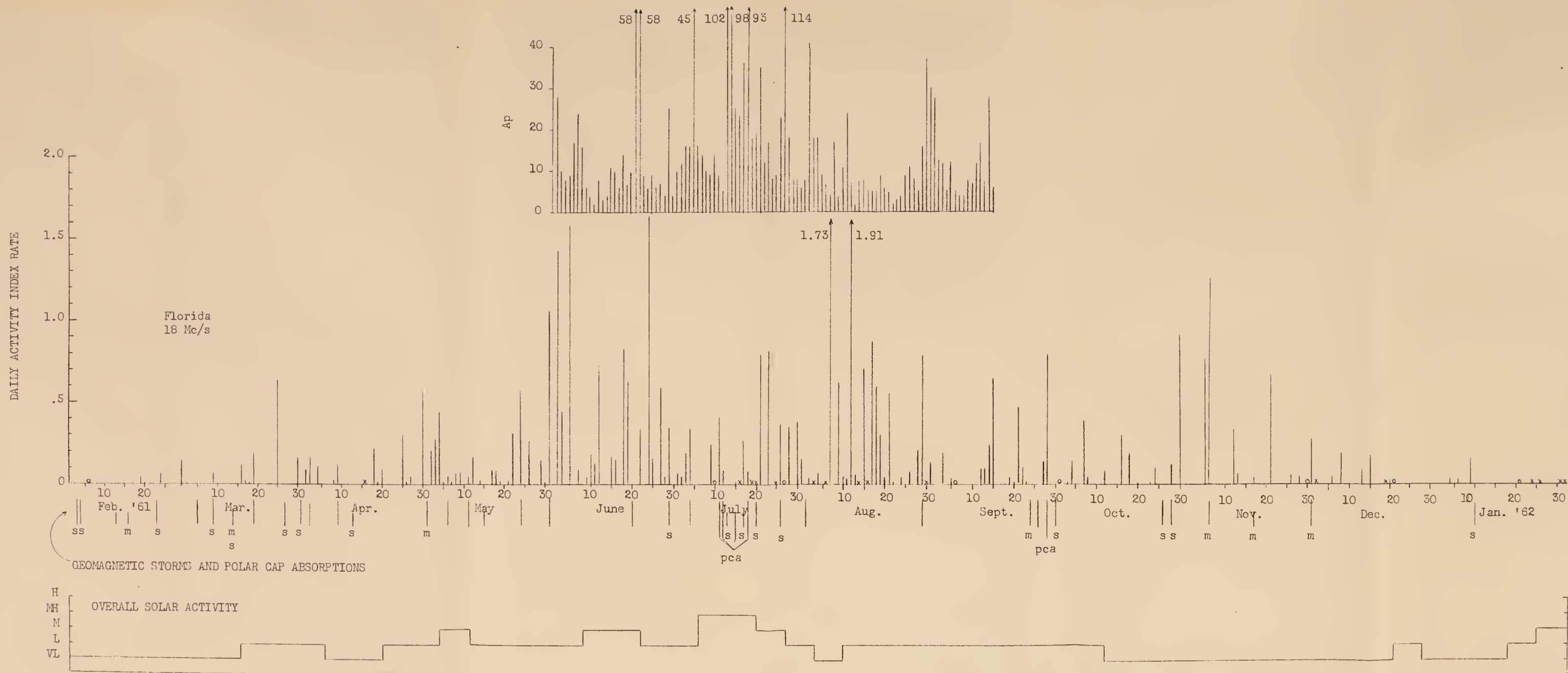


Figure 81.--Geomagnetic index Ap, Jupiter activity index rate, geomagnetic storms, polar cap absorptions, and overall solar activity in 1961.

TABLE 15

Solar Particles and Jupiter Emission around Opposition in 1961

Solar flare Date	Solar flare Importance number	Geomagnetic storm date	Particle travel time Sun to Earth	Earth to Jupiter	Date of particle arrival at Jupiter	Status of Jovian activity on date of particle arrival
July 11	3	July 13	42 hours	176 hours	July 20	Interference at Fla. station; strong Jupiter activity in Chile.
July 12	3	July 14	45 hours	188 hours	July 21-22	Moderately strong activity.
July 15	3 +	July 17	52 hours	218 hours	July 26	Moderate activity.
July 18	3 +	July 20	41 hours	172 hours	July 27	No watch in Fla.; moderate activity in Chile.
July 24	3 +	July 26	50 hours	210 hours	August 4-5	Very weak activity in Fla.; moderate in Chile.

in Figures 34, 35, 36, 37, 38, and 81, however, reveals that there were very few dates during this period when Jupiter was not active. Although in the five cases analyzed the geomagnetic storms were associated with Jovian decameter radiation, there were many nights of strong Jupiter emission which were not associated with geomagnetic activity. Perhaps these cases were due to solar plasma which did not pass close enough to the earth to stimulate magnetic activity. It does appear that the situation has changed from that of 1960. In 1961 there were fewer flare-stimulated geomagnetic events and more Jupiter activity. Although there are five examples of an approximate 8-day delay between geomagnetic storms and Jupiter emission, there is also evidence of a 3- to 4-day lag between Ap variations and Jovian radiation. Certainly the problem has not been cleared up; if anything, it has become more cloudy.

Polar Cap Absorptions

Certain solar flares are followed a few minutes to two hours later by radio frequency absorption in the earth's polar regions. It is believed that solar protons in the energy range 30 - 100 Mev., having been ejected from the sun, follow complex paths and spiral in along the earth's magnetic field lines, reaching the lower ionosphere near the magnetic poles where they ionize atoms and molecules, producing polar cap absorption (52). The proton transit times are longest near the peak of solar activity. In Figure 81 the dates of five pca events are marked (51). On all of these dates there was Jupiter activity. Table 16 summarizes the data.

TABLE 16

Polar Cap Absorptions in 1961

Date of pca event	Importance number of observed flare	Jupiter decameter activity
July 11	3	One hour of activity.
July 12	3	Weak activity lasting 15 minutes.
July 15	3 +	Very weak activity lasting 5 minutes.
July 18	3 +	Moderately strong activity lasting 30 minutes in Chile.
September 28	3 +	Strong activity lasting 30 minutes.

Three of the five pca events of 1961 occurred on days of strong decameter activity. In 1960 the correlation was not as good, with only four out of eight pca events occurring on the same day as Jovian emission. It should be pointed out, however, that the four pca's not followed by Jupiter emission happened far from opposition. (The 1960 pca data were obtained from reference 53.) Since interest is being aroused in pca events, more data should be available in the future from which to perform a more profitable study of the possible influence of relatively high-energy protons on the decameter emission process.

Overall Solar Activity

At the bottom of Figure 81 appears a graph of overall solar activity during the 1961 apparition of Jupiter. The abbreviations on the ordinate axis stand for the following: H - high, MH - moderately

high, M - moderate, L - low, and VL - very low. These data were obtained from the weekly bulletins of solar activity, reference 51.

One feature should be noted. The dip in Jupiter activity around opposition coincides with the moderately high level of solar activity. The explanation in Chapter II that the deviation of solar plasma by the earth's magnetosphere was the cause of the decline in Jovian activity at opposition is still considered valid by the writer; however, increased solar activity could very logically be an influencing factor. This should be tested using the 1962 data.

Conclusions Regarding Short-Term Correlations

The search for correlations between solar variables and the decameter emission has been made in hopes of testing the theory attributing the excitation of the Jovian noise to the arrival at the planet of solar plasma, which reacts directly with the magnetosphere producing magnetohydrodynamic waves or plasma oscillations, or supplies trapped particles which emit cyclotron radiation. Warwick (47) has found a peak in Jovian activity one day after solar continuum, and a higher than average probability of emission in the 10 days following solar continuum. The Florida group discovered an 8-day delay between geomagnetic storms and Jovian emission around opposition in 1960. The analysis of the 1961 data in this chapter appears to have turned up a contradiction. The Chree analysis of the geomagnetic index shows a maximum three days before strong Jupiter radiation, whereas the solar flare analysis indicates a null in solar flare activity 7 to 12 days before outbursts of radio noise from Jupiter. There is no short-term

correlation between sunspot number and Jovian emission. The geomagnetic storm correlation during 1961 is inconclusive and the role of high energy protons arriving at Jupiter as indicated by pca events on Earth at opposition has not been ascertained. The question of short-term correlations between solar variables and Jupiter's decameter radiation is obviously far from settled. The continuance of this study is deemed of utmost importance in establishing the sun's role in supplying the energy and/or particles responsible for the sporadic bursts of radio noise from the giant planet.

CHAPTER IV

ORIGIN OF THE NON-THERMAL JOVIAN RADIO EMISSION

The first part of the present chapter is an up-to-date summary of the experimental data collected by monitoring the non-thermal radio-frequency signals from the planet Jupiter. The last part of the chapter is a discussion of the theories which attempt to explain the origin of the decameter component of the radiation, in the light of these data.

Characteristics of the Radiation

As mentioned earlier, the decameter-wavelength radio noise from Jupiter was discovered in 1955, and the seven years of research since that time have yielded empirical evidence which has raised more questions than answers and suggests that a number of phenomena might be occurring in the Jovian environment. In contrast, the microwave or decimeter-wavelength radiation was not discovered until 1958, yet the data obtained in the intervening period with the use of large parabolic "collectors" has established several of the critical parameters and almost completed the picture with respect to the origin of these emissions.

Table 17 lists the characteristics of the non-thermal radiation from Jupiter. Although the decameter component is the subject of this study, the characteristics of the enhanced microwave radiation are included for comparison and will be commented upon briefly.

TABLE 17
Characteristics of the Non-Thermal Radio Emission from Jupiter

Parameter	Decameter Radiation	Microwave Radiation
Observed frequency range	4.8 - 38.5 Mc/s	440 - 9,900 Mc/s
Temporal behavior	Sporadic bursts of pulses lasting 0.03 - 10 sec.; heard a fraction of the good listening time with higher frequencies heard the least	Constant (no pulses)
Dynamic spectrum	Pulses have bandwidths ranging from a few tenths of a Mc/s to 3 or 4 Mc/s; at times fine structure is evident; center of activity drifts at the rate of 0.01 to several Mc/s per minute, drifts downward in frequency are predominant	Continuous spectrum
Polarization	Circular or elliptical, predominantly right-handed; apparent increase in the proportion of the pulses in which the left-hand component exceeds the right-hand one as the frequency is decreased	Mixed linear (30 percent) and random (70 percent); no significant variation in polarization with frequency; most intense polarization comes from regions 3 radii from the central meridian in the east and west directions
Correlation with rotation of Jupiter	Marked dependence of probability of occurrence on Jovian longitude; no apparent correlation of intensity with longitude; slight differences in the average polarizations of the pulses from the three sources	Intensity correlated with Jovian longitude; oscillation of the plane of polarization

TABLE 17--Continued

Parameter	Decameter Radiation	Microwave Radiation
Overall spectrum	Flux density decreases with an increase in frequency	Nearly flat from 3 cm to 68 cm
Maximum flux density received	10^{-18} w/m ² /cps (at 5 Mc/s)	10^{-25} w/m ² /cps
Long-term variability	Apparent correlation with elongation of Jupiter; evidence of 8- and 32-day cycles; inverse correlation of planet-wide probability of occurrence with sunspot cycle; relation to solar activity still speculative	Decrease in flux density from 1958 to 1959; relationship to solar activity uncertain
Source dimensions	Unknown	Radiation belt region 3 x 1 optical diameters in equatorial and polar directions; no apparent change in size with frequency

Observed Frequency Range

Decameter. The low frequency limit in the decameter range is due to the opacity of the earth's ionosphere. The critical frequency of a layer of ionization is determined by the electron density. At the Florida station the critical frequency is rarely below 10 Mc/s. When the critical frequency for normal incidence is 10 Mc/s, then extra-terrestrial radiation of frequency less than 10 Mc/s will be refracted back into interplanetary space, while terrestrial radiation of frequency less than 10 Mc/s will be trapped under the ionosphere. Higher frequencies incident obliquely on the layer of maximum electron density may also undergo total internal reflection. Thus, at low frequencies, terrestrial radio noise makes detection of the Jovian signals quite difficult. In addition to this, the low frequencies are attenuated more than the high frequencies in passing through a layer of ionization, because the wave frequency is closer to the collision frequency of the electrons with ions and molecules. The E field of an impressed harmonic wave causes the electrons and ions in the ionosphere to execute forced oscillations. The fields of the moving electrons modify the incident wave. (The movement of the ions is negligible.) When the ordered motion of an electron is destroyed by a collision, some of the energy of the wave is dissipated and the wave suffers absorptive attenuation (54, 55). Absorption approaches a maximum as the refractive index approaches a minimum (56).

On several occasions during 1961, the critical frequency of the layer of maximum electron density in the ionosphere over the Chile station dropped below 5 Mc/s, permitting measurement of the 5 Mc/s

Jovian emission. On the majority of the nights, the listening conditions were very poor due to atmospheric and man-made noise, but on 4 nights there was unmistakable reception of Jovian signals at 5 Mc/s. Ellis has reported receiving Jupiter radiation in Tasmania at 4.8 Mc/s (57). It is quite probable that the non-thermal radiation extends to much lower frequencies, and as solar activity declines toward the expected minimum in 1964-1965, low-frequency measurements should become more profitable (58). However, the search for much lower frequency signals will have to be made from the far side of our ionosphere.

The highest frequency signal that has been recorded in the decameter range is 38.5 Mc/s. This signal was recorded by J. W. Warwick (29) on October 5, 1961, using swept-frequency equipment which had an upper limit of 41 Mc/s. Five times in 1961 Warwick recorded Jovian radiation above 35 Mc/s. J. D. Kraus reported a single unrecorded audio observation at 43 Mc/s on March 2, 1957 (59). F. G. Smith could detect no emission from Jupiter at 38 and 85.1 Mc/s, and he concluded that if the signals were present the flux densities must be less than 10^{-24} and 3×10^{-26} $\text{w/m}^2/\text{cps}$ respectively (60). The fact that Smith's recording system had a time constant of 6 seconds casts doubt on the validity of his conclusions. During 1961 the Florida group monitored Jovian signals at 31 Mc/s. The results were presented in Chapter II. The higher the frequency in the decameter range, the less frequent is the occurrence of Jovian noise storms. This statement is well supported by the 1961 data, as shown in Figure 82. Here the percentage of nights that Jovian signals were received is plotted as a function of frequency. Notice the rapid decline in the amount of

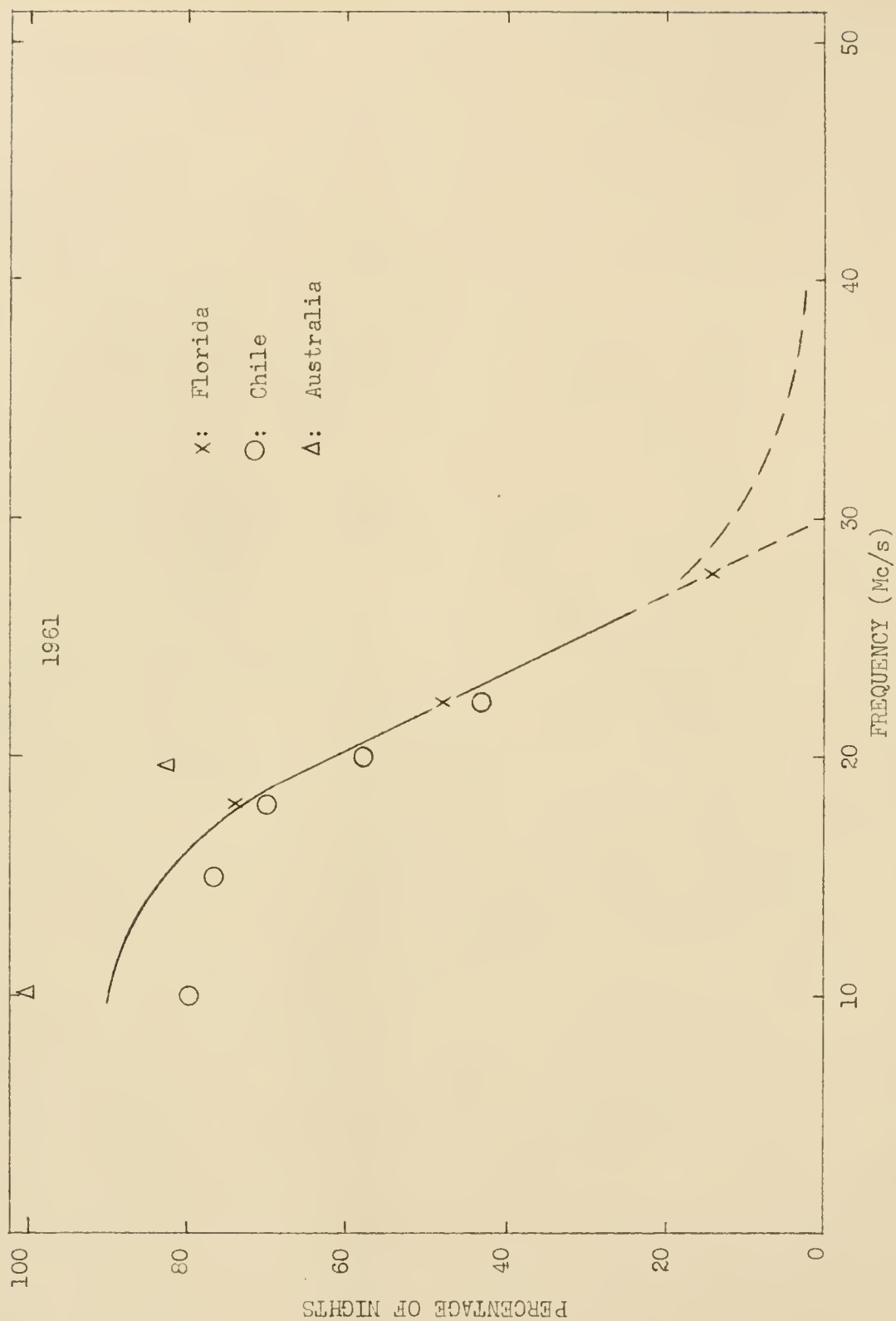


Figure 82.--The frequency of occurrence of Jovian radio noise as a function of frequency.

decameter radiation received at frequencies above 20 Mc/s. The points on this graph represent data collected in Florida, Chile, and Australia. The higher percentage of 10 Mc/s radiation at the Australian station is probably caused by the greater transparency of the nighttime ionosphere there. This is borne out by the lower values of critical frequency, which are published in the ionospheric bulletins (23). The antenna operating at 19.7 Mc/s in Australia is of very high gain; hence, the higher percentage in that case. The dashed lines are extrapolations to frequencies above 27.6 Mc/s and indicate a cutoff frequency in the neighborhood of 30 Mc/s or a gradual decrease in the percentage of reception out to about 40 Mc/s. Which of these extrapolations best fits the physical situation has not yet been determined. An elaborate antenna system of considerable gain is now under construction at the Florida station, the purpose being to detect planetary radiation at 51 Mc/s. Since galactic noise decreases with increasing frequency (61), the interference problems are minimized. It appears that the high frequency limit in the decameter range is a property of the radiation itself. Further evidence which supports this conclusion is the manner in which the intensity of the radiation decreases with an increase in frequency. This will be demonstrated later in this chapter when the overall spectrum is examined.

Microwave. Curiously enough, there exists between the decameter radiation and the microwave component of the Jovian emission a gap of an entire frequency decade in which no radiation has been detected. The lowest frequency at which the non-thermal microwave component has been detected is 440 Mc/s (62). At the high frequency

end of the microwave range the radiation seems to conform to thermal radiation, that is, the flux decreases with wavelength as λ^{-2} . The upper limit of the non-thermal component is not well defined, but it is probably close to 9,900 Mc/s (63). Hence the high frequency limit is imposed by the thermal emission, and the low frequency limit is due to equipment limitations, notably the lack of large antennas possessing high gain characteristics which permit the detection of low flux levels.

Temporal Behavior

Decameter. The long wavelength radiation from Jupiter occurs in sporadic bursts or storms which are composed of noise pulses having durations from 0.03 to 10 seconds. Figure 83 shows a typical low speed recording (6 inches per hour) of a Jupiter noise storm on 18 Mc/s. The constant deflection of three major divisions is caused by the radio noise from the galaxy and the Jovian pulses are superimposed on this background. Notice the sporadic nature of the pulses. It is impossible to measure the pulse durations on the low speed recordings. The storm shown lasted almost one hour. The marks at the base of the record were synchronized with the WWV time signal. As the record indicates, the decameter noise is detected only a fraction of the time, and higher frequencies are heard the least (see Figure 82).

Immediately following the discovery of the decameter radiation from Jupiter, J. D. Kraus [64] and R. M Gallet (65) reported receiving pulses having durations of only a few milliseconds. Kraus found the durations to be of the order of tens of milliseconds, while Gallet, with the help of photographic records made with a cathode-ray oscilloscope, recorded pulses as short as a few milliseconds. This type of

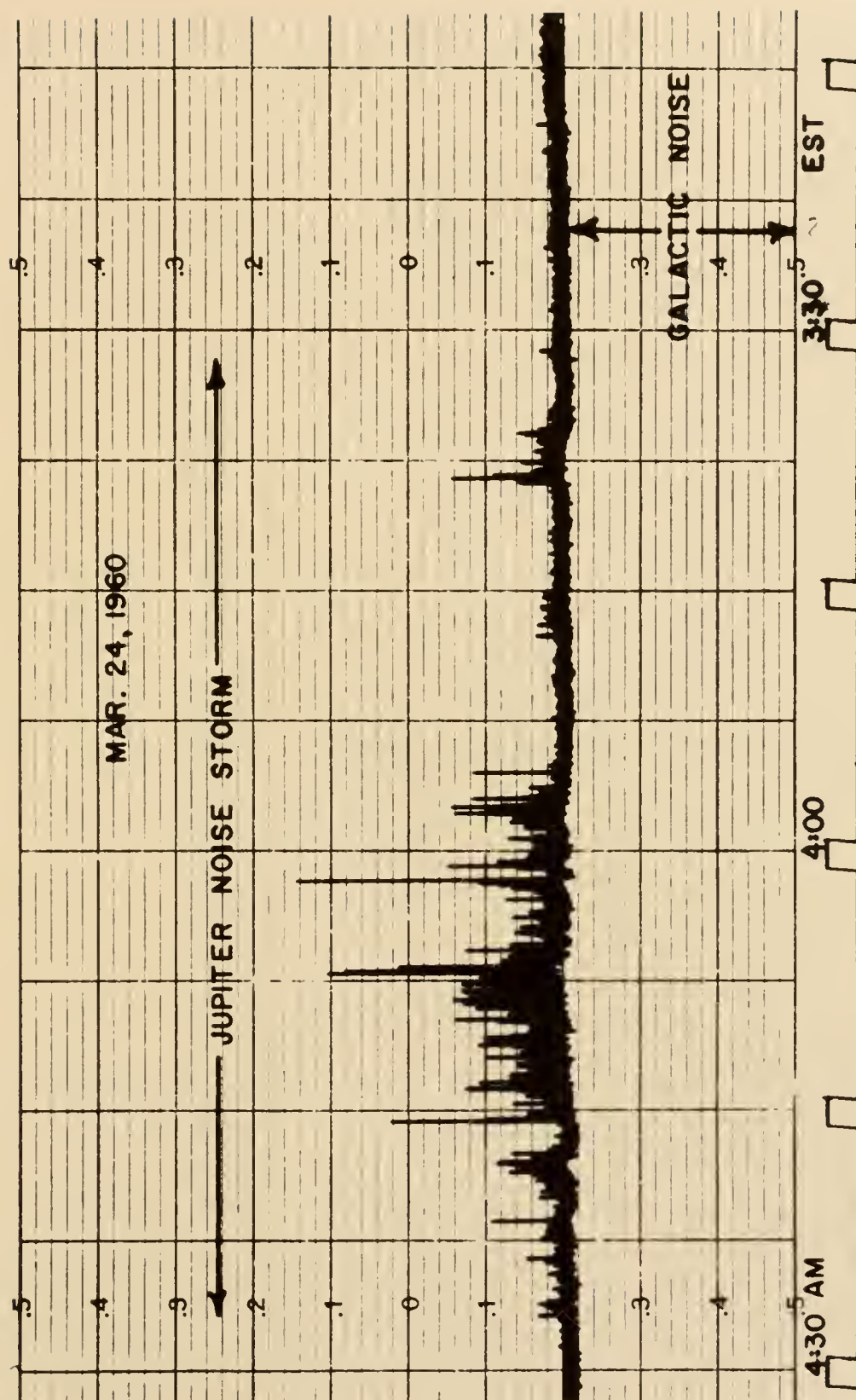


Figure 83.--Typical low speed recording of a Jupiter noise storm on 18 Mc/s.

signal was not heard again for several years, but in 1961 it began to reappear and was recognized by the Florida group and by Douglas and Smith (66). Figure 84 shows a comparison of the short pulses with the normal pulses (ranging from several tenths of a second to several seconds). Each horizontal division represents one second of time, and the frequency in both records is 18 Mc/s. In a loudspeaker the short pulses produce a rapid popping sound that contrasts strongly with the swishing noise characterizing the normal radiation. On occasion the normal and short pulses have been observed during the same Jupiter storm. The short pulses are not detected as often as are the normal pulses; however, the short pulses have been more abundant in 1962 than in the four previous years. The shortest pulses in Figure 84 have durations of about 0.05 second. In Chile rapid popping Jupiter radiation has been recorded at a rate of about 30 pulses per second. These durations are still somewhat greater than the millisecond pulses recorded in 1956, which have not been reconfirmed since that time. A recent determination of the response time of the high speed recording system at the Florida station yielded a value of 3 milliseconds; thus it is believed that the shorter pulses could have been detected had they occurred.

The longest duration pulses last about 10 seconds and are observed only rarely. They have been detected in Florida and Chile at widely separated frequencies.

One of the major questions concerning the decameter radiation is the extent to which the terrestrial ionosphere modifies or creates the pulse structure of the signals. A comparison of the records taken

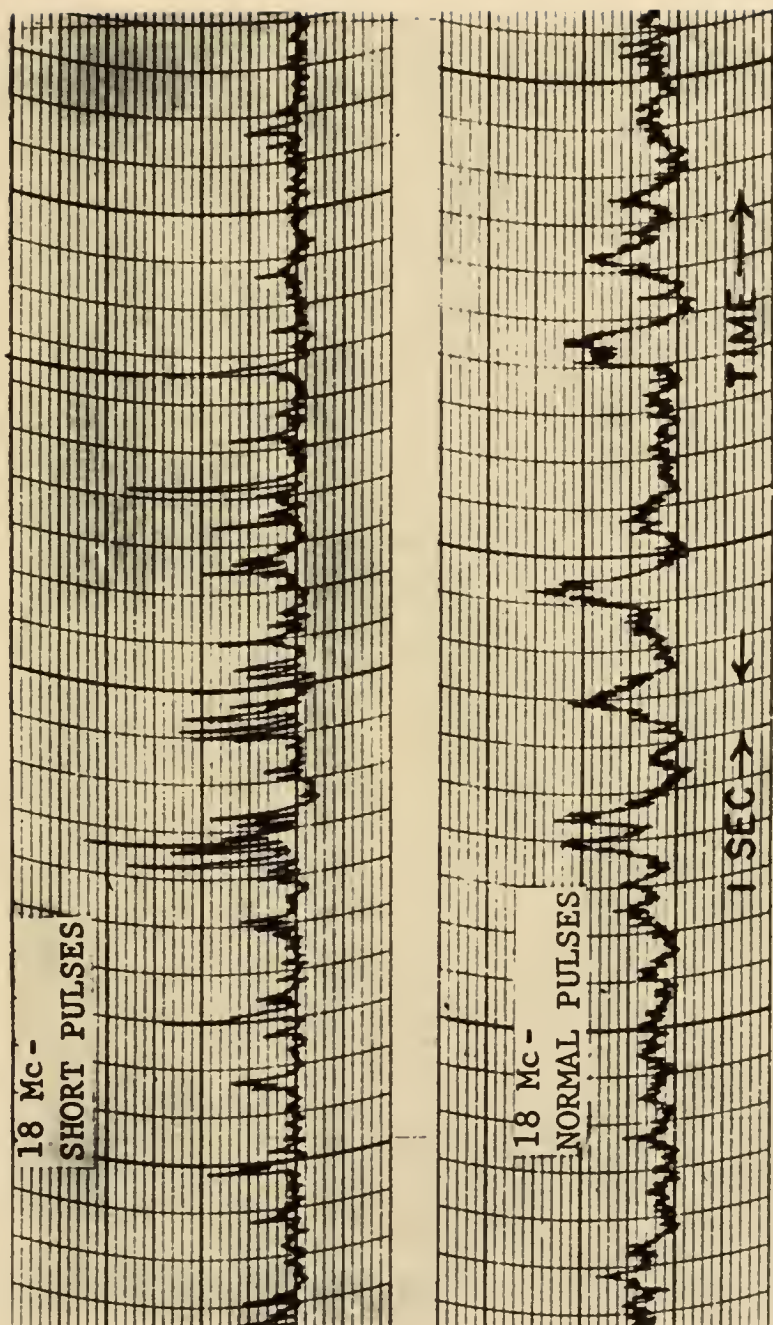


Figure 84.--Comparison of short and normal pulses of Jovian radiation at 18 Mc/s. The upper record was made at the Florida station on June 15, 1962. The bottom recording was taken in Chile on April 30, 1961.

at two stations shows that there is good time correlation between the Jovian decameter storms, but usually very poor pulse to pulse correlation. Figure 85 shows such a period of poor correlation of pulses on records obtained using a chart speed of 5 mm./sec. at stations separated by 7,040 km. Notice the single pulse "a" which is replaced in the lower record by a series of five or six peaks. The distortion of the individual pulse shapes suggests the presence of a very rapid scintillation component with a period comparable to the durations of the pulses (67). Gardner and Shain noticed the same lack of correlation in records made only 25 km. apart and concluded that the main features of the received signal are attributable to a strong scintillation effect caused by changing irregularities in the transmission medium (26). Gallet has pointed out that the alterations in the apparent length of the pulses are possible consequences of the ionization of the interplanetary medium (24).

In contrast to the lack of correlation usually found in simultaneous observations, there have been a few cases of good pulse to pulse correlation. Figure 86 shows such a period of reasonably good correlation. The letters will aid the reader in recognizing the more obvious correlations. Douglas and Smith have found cases of excellent pulse to pulse correlation on simultaneous records made at stations separated by 15, 30, and 100 km. (66, 68). They conclude that the fine structure of the radiation is characteristic of the source or the interplanetary medium but is often obliterated by local ionospheric effects. More recently they have at least orally reversed this stand.

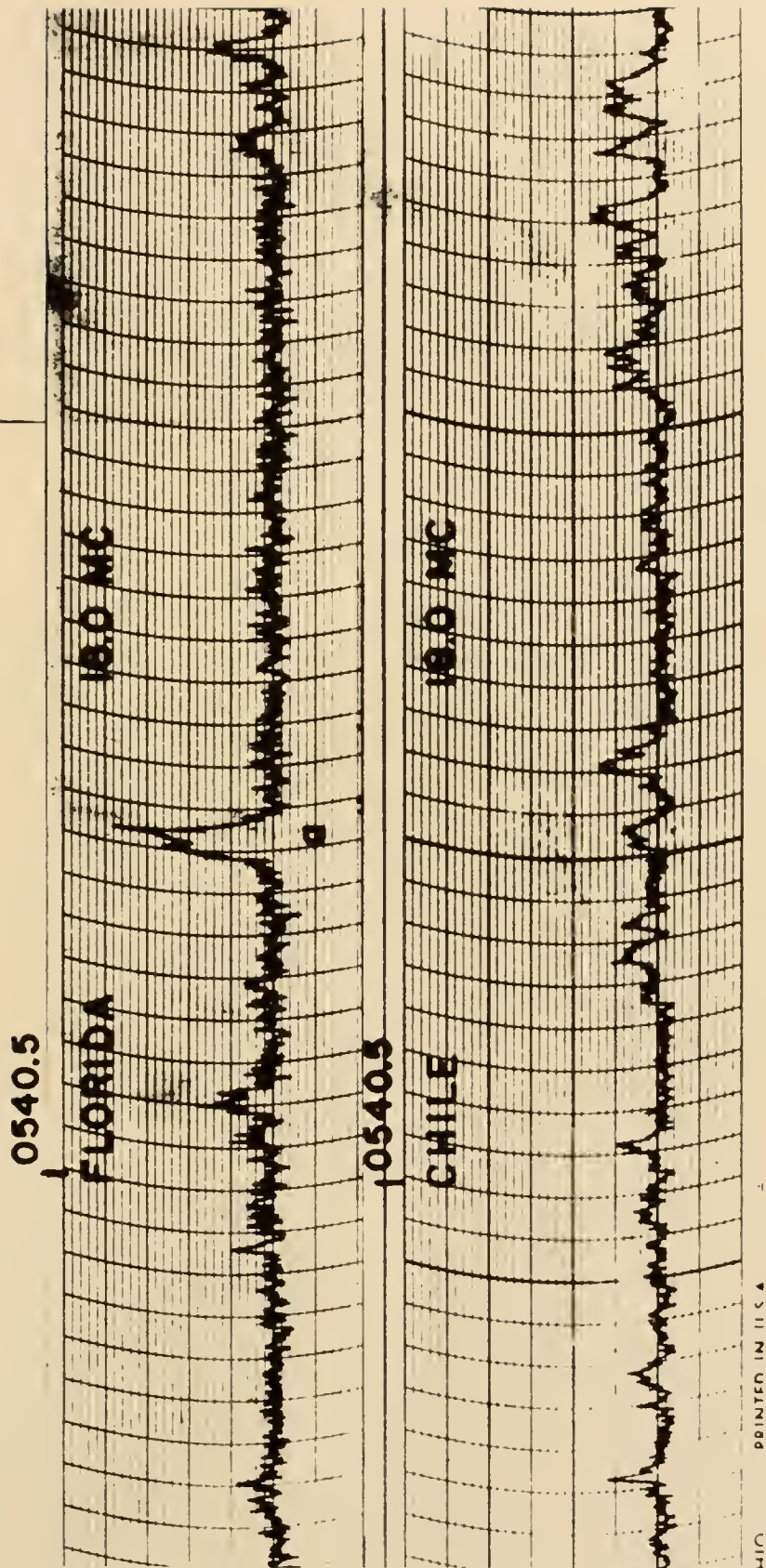


Figure 85.--Poor time correlation of pulses on the Florida and Chile records of March 24, 1960. Approximate time is 5h. 40m. a.m. Eastern Standard Time.

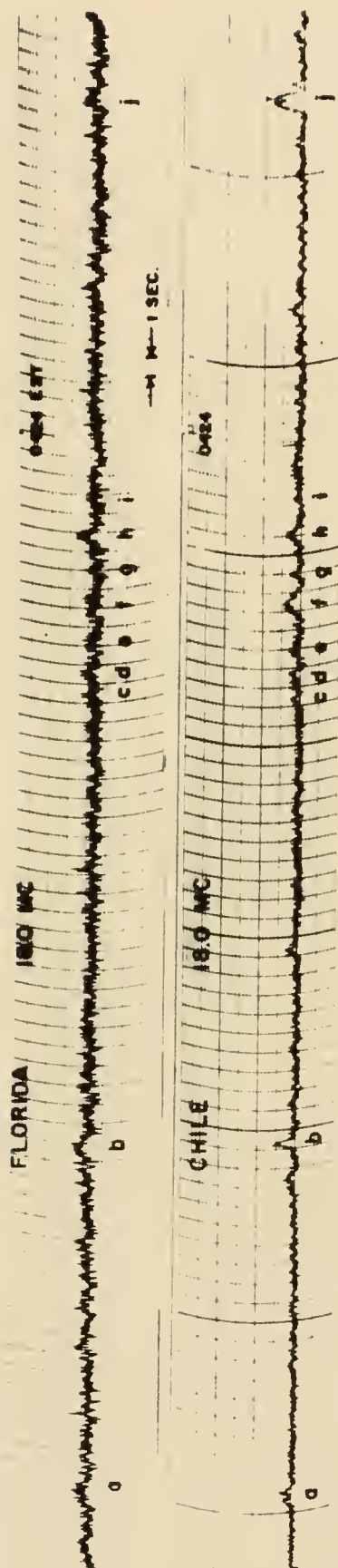


Figure 86.--Period of good correlation from the records of March 29, 1960, taken at the Florida and Chile stations. Approximate time is 4h. 24m. a.m. Eastern Standard Time.

Often there have been interruptions in the reception of Jupiter noise at one or the other of the University of Florida stations. Figure 87 shows such a period of alternate fading in Florida and Chile. The periods of the scintillations are of the same order as the scintillations of the radio stars, which are generally attributed to drifting clouds of ions in the ionosphere (69). Much of the tendency of the Jovian signals to appear as short trains of pulses is probably due to this slower terrestrial scintillation component having a period of 30 or 40 seconds (67).

A recent analysis of 1961 high speed recordings has been performed by W. Mock of the Florida group. The preliminary results indicate that the pulses of 0.3 second duration and longer that were received in Chile and Florida come from the same statistical population, implying that they originate in the Jovian environment. A similar analysis on the pulses of shorter duration is still in progress.

In summary, it appears that the basic pulse originates on Jupiter and that a rapid terrestrial scintillation component distorts the shape of the pulses and a slower scintillation component is responsible for the bunching of the pulses or the burstiness of the radiation. This is essentially the same conclusion that was reported in 1960 after analyzing the Florida and Chile data of that year (67).

Microwave. Within the precision of present measurements, the microwave energy appears to be constant over long periods of time. There are indications of slight variations in intensity that are correlated with the rotation of Jupiter. This will be discussed later in the text.

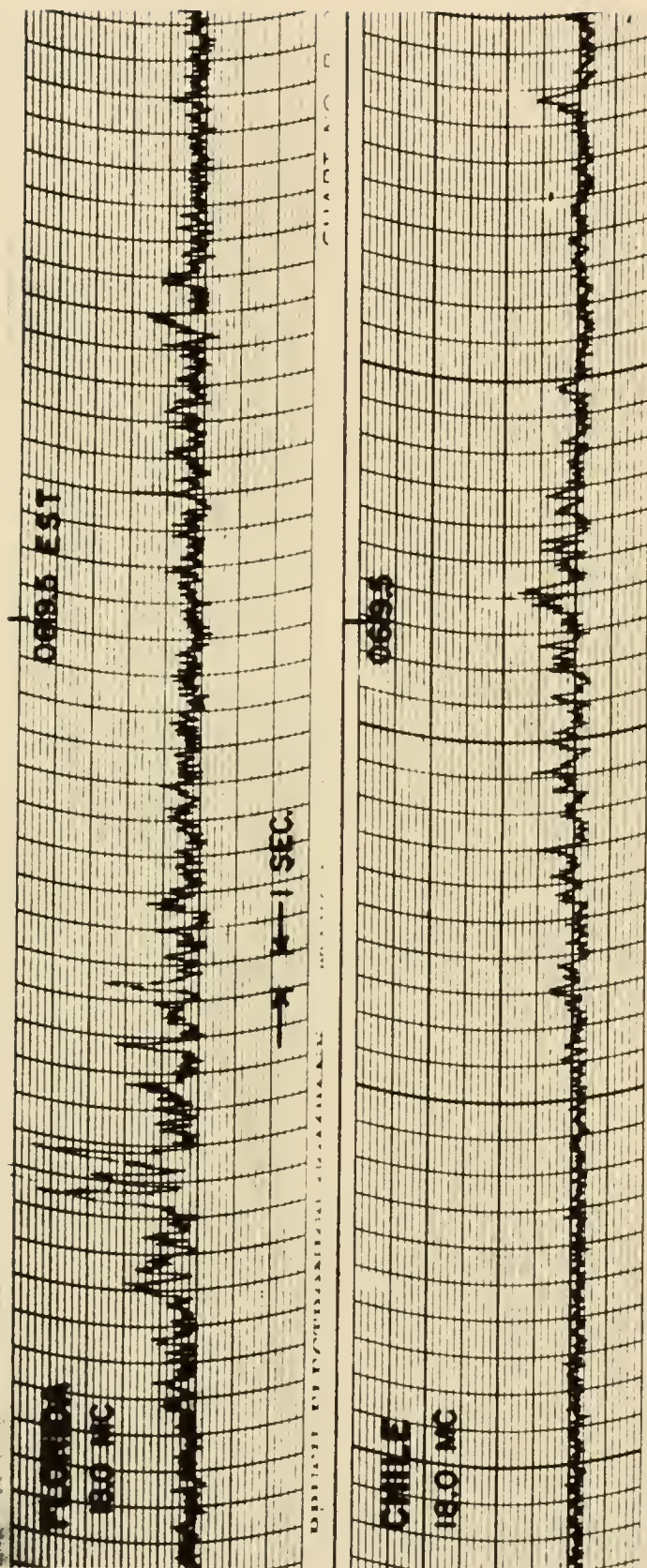


Figure 87.--Alternate fading or out-of-phase scintillations from the records of March 23, 1960. Approximate time is 6h. 19m. a.m. Eastern Standard Time.

Dynamic Spectrum

Decameter. The bandwidth of the decameter pulses is highly variable, ranging from a few tenths to 3 or 4 Mc/s, and the part of the spectrum occupied by all the pulses in a given noise storm is somewhat wider (70). Several different pulse types have been recognized, and are illustrated in the dynamic spectra shown in Figures 88 through 90. Figure 88 shows the build-up and decay of an ordinary pulse. The envelope of this pulse is quite smooth, which at times is typical. The total period of build-up and decay is approximately 3 seconds. Since the ordinate is linear with respect to the signal voltage, the half-power bandwidth of the pulse at its maximum development is about 1.7 Mc/s. Pulses of this type, broad and smooth, were common in 1961. H. J. Smith, Lasker, and Douglas observed similar pulses in 1960 (71).

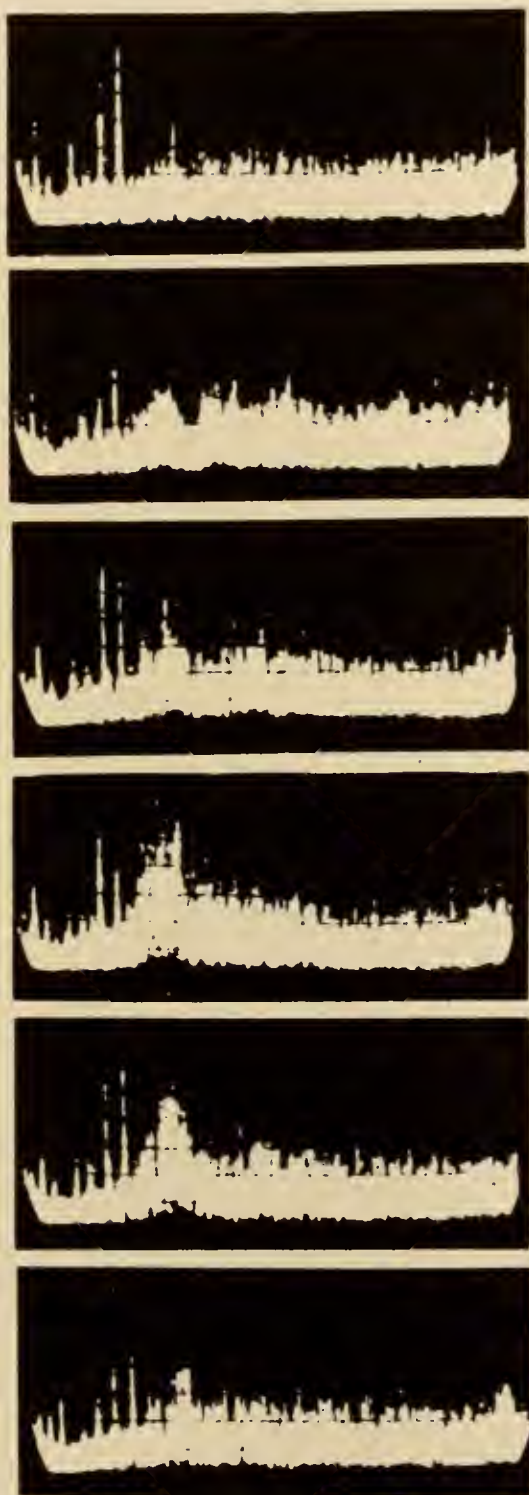
Figure 89 shows the spectral characteristics of single and multiple peaks extending over only a few tenths of a Mc/s (2). The A pulse has a half-power bandwidth of about 0.4 Mc/s. The B pulse, following 6 seconds later, has a half-power bandwidth of about 0.2 Mc/s. Notice that it is double. Often the pulses display higher multiplicity.

Figure 90 shows the dynamic spectrum of a Jovian pulse exhibiting a regular fine structure resembling closely-spaced harmonics (12). This type of pulse structure is observed a very small proportion of the time compared with the frequency of occurrence of the pulse types shown in Figures 88 and 89. It is believed that this fine structure is related to the pulses having durations of tens of milliseconds. W. F. Block of the Florida group is in the process of analyzing



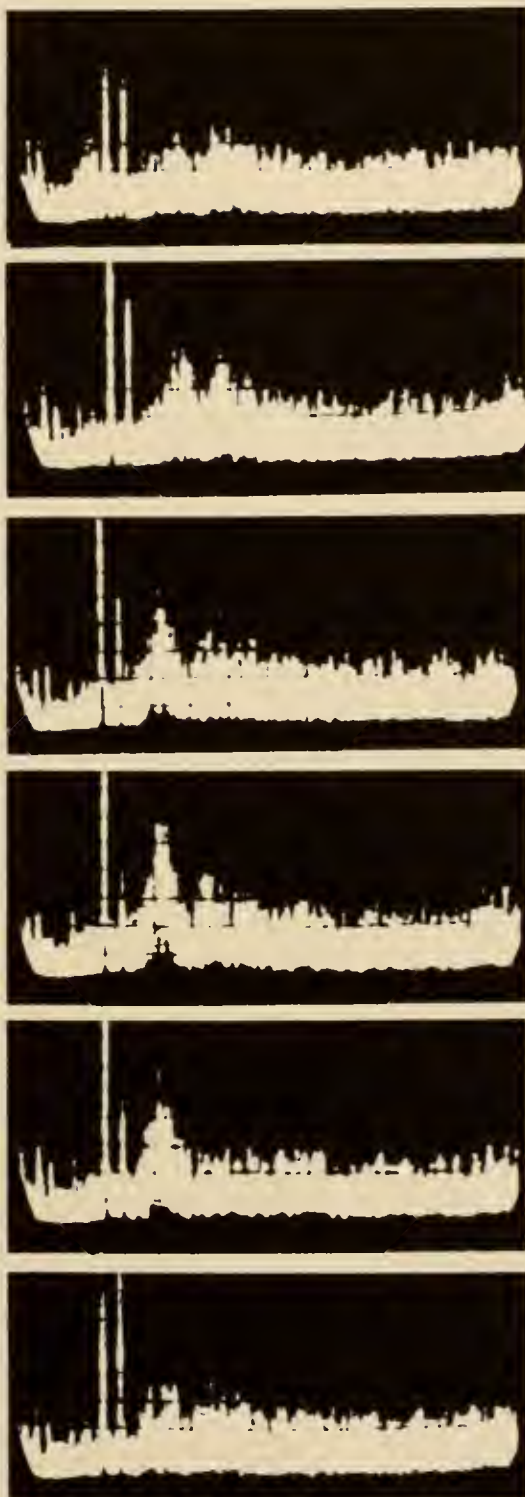
Figure 88.--Build-up and decay of an ordinary pulse of Jupiter noise. Time increases downward in each column at the rate of 1/4 second per frame. The deflection in the initial frame (top left) is caused by the radio noise from our galaxy.

(A)



16 17 18 19 20
FREQUENCY IN MC

(B)



16 17 18 19 20
FREQUENCY IN MC

Figure 89.--Spectrograms of two Jovian noise pulses. The narrow spikes to the left of the pulses are signals from radio stations. Time increases downward in each column at the rate of 1/2 second per frame.

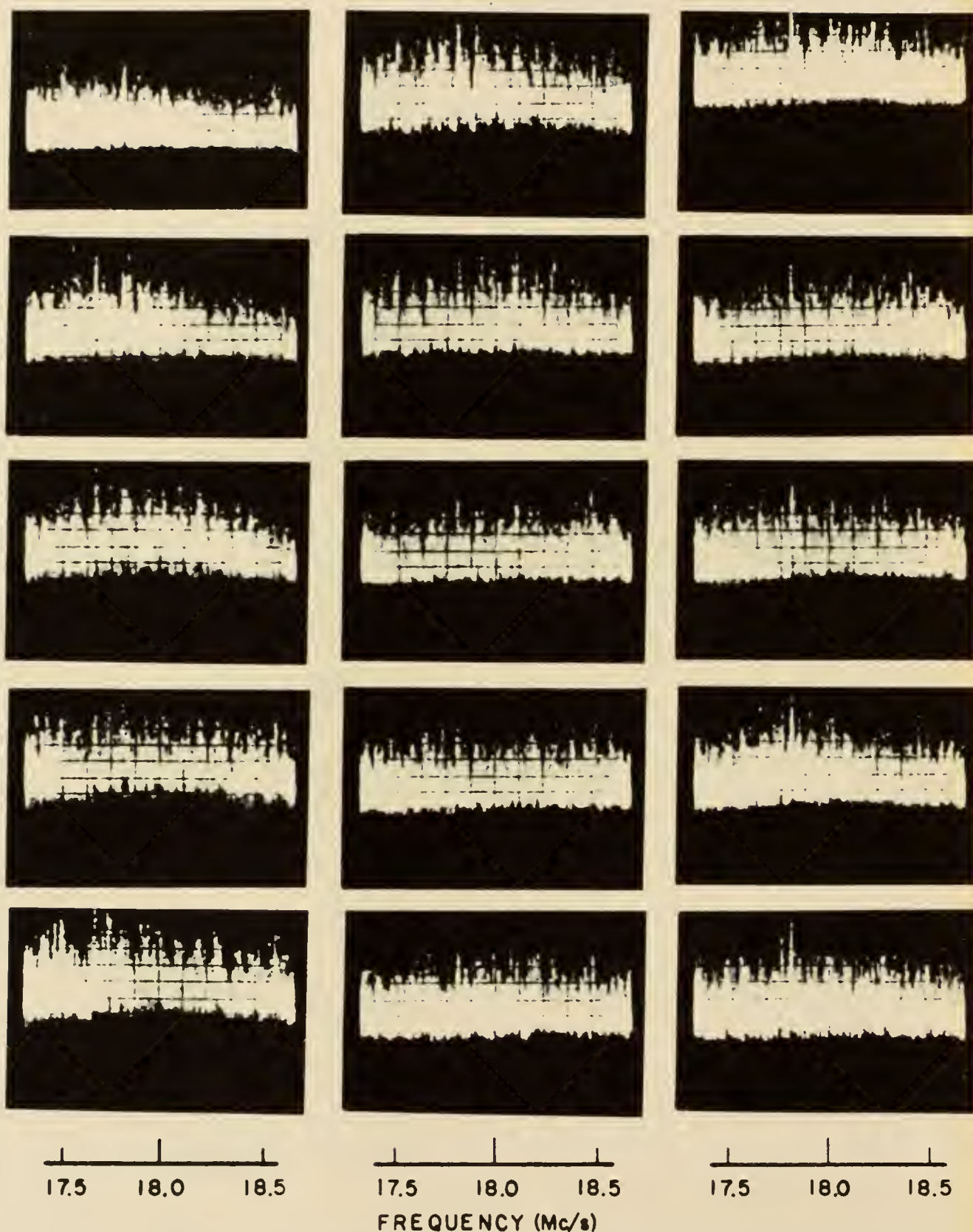


Figure 90.--Dynamic spectrum of a Jovian pulse exhibiting fine structure. Time increases downward in each column at the rate of 1/4 second per frame.

thousands of feet of 16 mm. film taken during 1961 and 1962 of the cathode-ray tube display of a swept-frequency receiver. Most certainly the result will be a better understanding of the apparent pulse structure of the Jovian radiation.

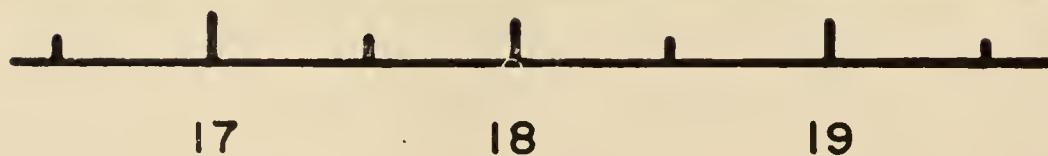
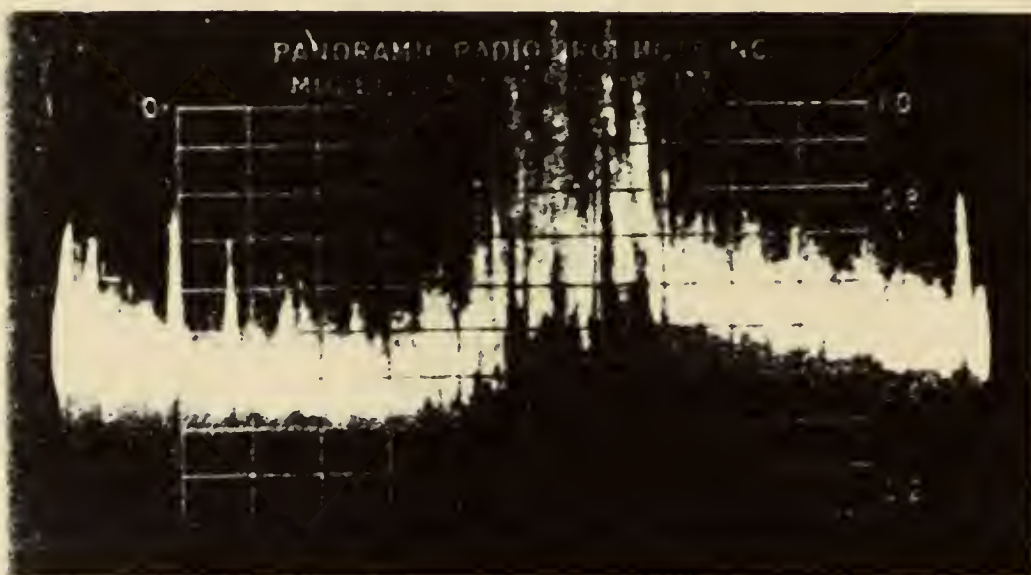
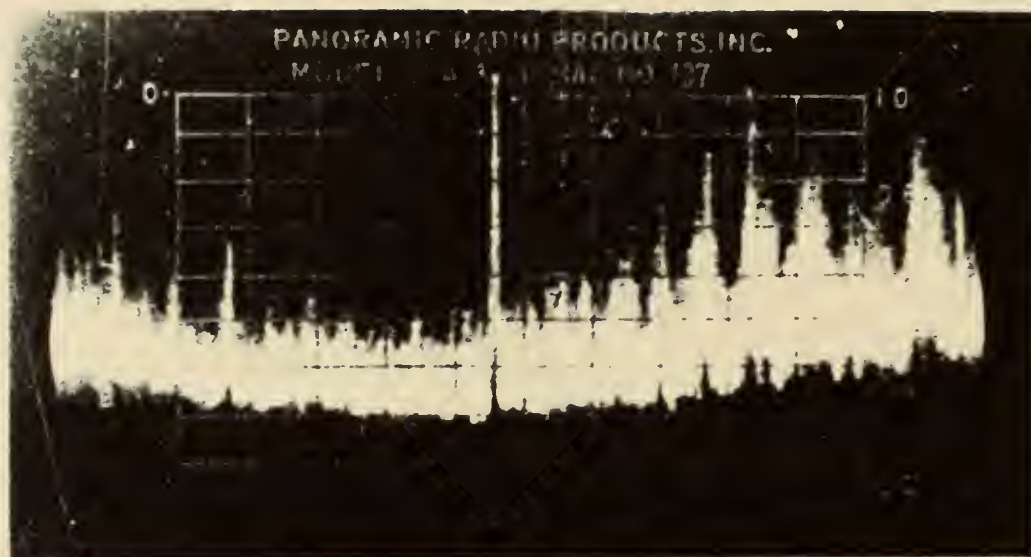
In many cases noise storms are detected which drift up or down the spectrum (2, 12, 29, 71). The observed drift rates vary, with the highest being several Mc/s per minute. Drifts downward in frequency seem to be predominant (12, 72). Figure 91 shows frames taken from the spectra of two bursts of short pulses which occurred several minutes apart. During the interval between bursts the center of activity has drifted downward nearly 1 Mc/s. The striking saw-tooth appearance is suggestive of harmonics of some highly resonant phenomenon (33).

Warwick has found evidence that the sense of the drifts are correlated with the System III longitude, drifts towards higher frequencies occurring early in association with source B, and drifts downward occurring late in association with source A (29).

Microwave. The microwave component of the Jovian emission is characterized by a continuous spectrum.

Polarization

Decameter. In 1956 Burke and Franklin observed that the 22.2 Mc/s radiation from Jupiter was circularly or elliptically polarized, most often in the right-handed sense (25). The same year Gardner and Shain, working in the southern hemisphere, obtained a single measurement which indicated right-hand circular polarization (26). During 1960 observations from Chile and Florida showed that the decameter



FREQUENCY (MC/S)

Figure 91.--Individual frames from the spectra of two bursts of short pulses which occurred several minutes apart. The narrow spikes at 17.9 Mc/s and at the left end of the trace are signals from radio stations.

radiation is nearly always circularly or elliptically polarized in the right-hand sense (2). The values of the axial ratio of the polarization ellipse for successive Jovian noise pulses usually exhibited a large random fluctuation, and the variation in the nightly averages of the axial-ratios for all pulses from source A was also large. The 1961 data, consisting of simultaneous observations from Chile and Florida using 22.2 Mc/s polarimeters, has revealed significant differences in the average axial-ratios recorded on a given date (7). Figure 92 demonstrates this effect. Each point represents the mean of all of the individual bursts observed at that station on the given date. The cause of these effects is not well understood, since they greatly exceed the effects to be expected from ionospheric electron densities of the usual order of magnitude.

Although the right-hand component is predominant, there are periods lasting several minutes when the radiation exhibits complete left-hand circular polarization (73). There is an apparent increase in the proportion of the pulses in which the left-hand component exceeds the right-hand one as the frequency is decreased. From an analysis of 1962 data collected in Chile, it has been found that at 22 Mc/s, 99.4 percent of the pulses were right-hand and 0.6 percent left-hand, while at 16 Mc/s, 67 percent were right-hand and 33 percent left-hand (74). C. H. Barrow has noticed this same effect in polarization measurements at 18.3 and 24 Mc/s (75). At the time of writing, 16 Mc/s is the lowest frequency at which polarization investigations have been made. There also seem to be significant differences in the average polarizations of the pulses from the three decameter sources (2, 73).

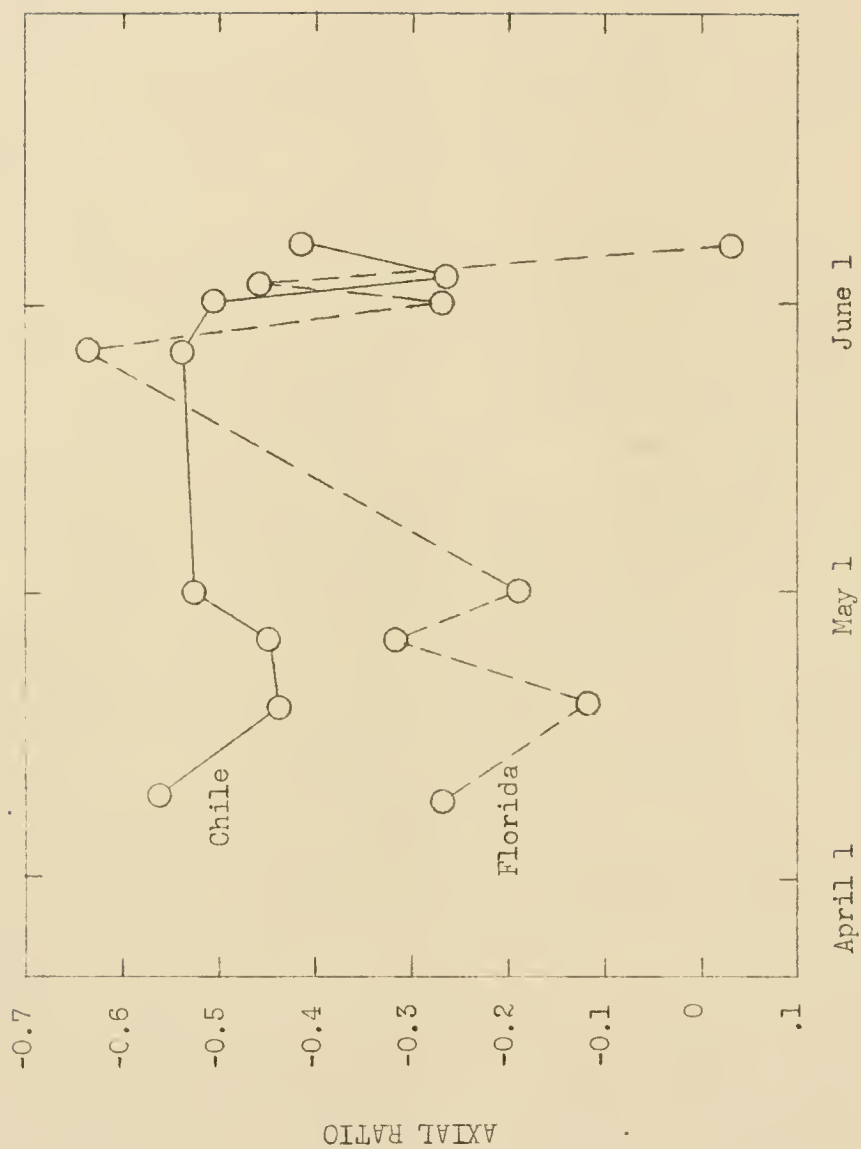


Figure 92.--Average axial-ratios of polarization ellipses at the two stations on different dates in 1961.

Due to the fact that the same polarization sense is observed from the two magnetic hemispheres of the earth, it is unlikely that the polarization arises in the terrestrial ionosphere. The other alternative is that the polarization originates in the neighborhood of Jupiter, lending evidence to the existence of a Jovian magnetic field. The data reviewed indicate that the decameter radiation possesses a characteristic pulse structure and usually right-hand elliptical polarization upon leaving the vicinity of Jupiter, but that modification occurs along the propagation path (73).

Microwave. In 1960 Radhakrishnan and Roberts discovered that the microwave emission from Jupiter consisted of a randomly polarized component comprising about 70 percent of the total and a linearly polarized component accounting for the remaining 30 percent with the electric vector approximately parallel to Jupiter's equator (76). Working at a wavelength of 31 cm., they found that the radiation was most intense and most intensely polarized at distances of the order of 3 radii from the axis of rotation. More recent measurements (77) indicate that there is no significant variation in polarization with frequency over the range 960 - 1390 Mc/s.

Correlation with Rotation of Jupiter

Decameter. There is a marked dependence of the decameter wavelength radiation on Jovian longitude. Probability histograms strongly imply the existence of three main sources whose locations in System III longitudes are A: 235° , B: 120° , and C: 310° at 18 Mc/s. The locations of the sources change with frequency, the higher frequencies being shifted to lower longitudes. Source B is broad and on

many of the histograms appears at least partially resolved, perhaps indicating the existence of two closely-spaced sources. In all cases the widths of the peaks on the histograms are less than 180° which has been interpreted as evidence that the sources have a directional character. As the frequency is increased, the three peaks become narrower. Source C disappears at 27.6 Mc/s, but at low frequencies it is more active than source B. The average separation of B and C is 176° . Source A is diametrically opposite a null on the probability histograms. The period of rotation of the decameter sources is essentially constant and has been determined by Douglas to be $9^h 55^m 29^s.37$ (22,78). An independent analysis by the Florida group yielded a value of $9^h 55^m 29^s.35$, which is in good agreement with Douglas (2). There does not appear to be any correlation between the intensity of the decameter emission and the rotation of Jupiter, although more investigation along this line would seem advisable. As mentioned in the previous section of the text, there appear to be significant differences in the axial ratios of the pulses of radiation from the three sources. A detailed discussion of the decameter source studies is found in Chapter II.

Microwave. Observations made at the California Institute of Technology indicate that the polarization plane of the microwave radiation rocks through an angle of about 18° in synchronism with the rotation of Jupiter (77). Figure 93 shows the orientation of the Jovian microwave halo region and the plane of polarization relative to the equatorial plane. This rocking of the plane of polarization has been interpreted as implying that the magnetic pole is displaced 9° from the axis of rotation.

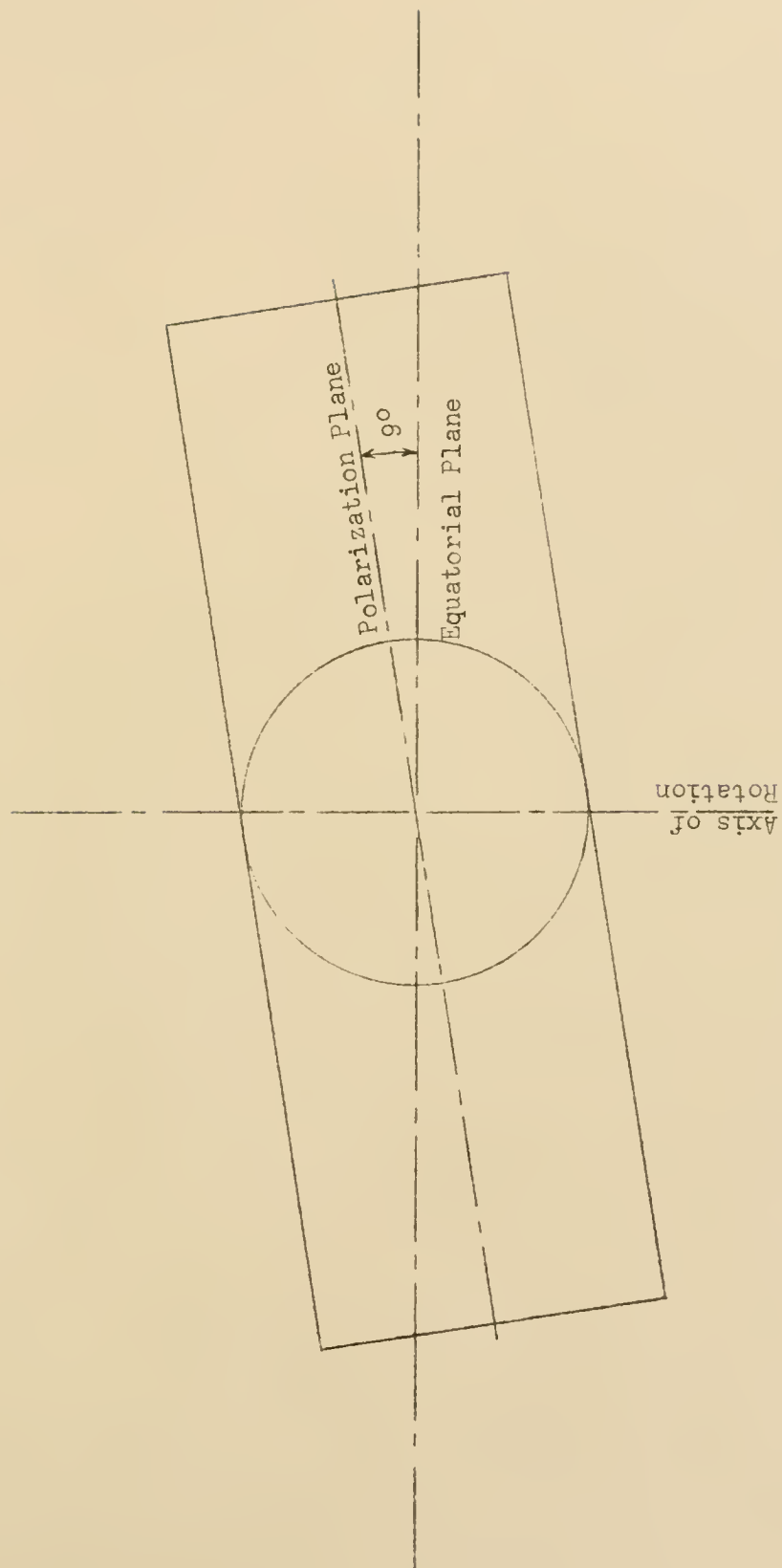


Figure 93.--The Jovian microwave halo and the orientation of the plane of polarization.

From early observations of the microwave emission, McClain and Sloanaker, working at 10.3 and 21 cm., reported finding suggestions of changes in the intensity of the radiation at nearly the System II period (79, 80, 81). Roberts and Stanley were unable to confirm these reports, for their measurements at 31 cm. showed no significant correlation of intensity variation with the System I or System II periods (82). Similarly, Drake and Hvatum (62) found no statistically significant correlation with rotation at 68 cm. More recently, investigations have turned up new evidence which shows variations in intensity which are correlated with the rotation of the planet (83). Morris and Berge (77), using Cal. Tech.'s twin 90-foot antennas operating as an interferometer, have found that the 1390 Mc/s radiation is more intense when the radiation belts are viewed from Jupiter's magnetic equatorial plane. The variation is correlated with the System III period and is greater than can be accounted for by rotation of the polarization plane. They conclude that the magnetic poles of Jupiter are at System III longitudes of 200° and 20° , with an uncertainty of about 10° . It is interesting to note that measurements at 27.6 Mc/s indicate that the center of the principal decameter source lies at about 225° , however, the second pole at 20° is very close to the longitude zone from which long-wavelength radiation is seldom received.

Overall Spectrum

Decameter. There have been few calibrated flux measurements made of the decameter radiation. Gardner and Shain determined that the largest pulses they had received at 19.7 Mc/s corresponded to a

flux density of 10^{-19} w/m²/cps (26). Carr calculated that at 18 Mc/s a flux level of 5×10^{-20} w/m²/cps was exceeded 11 percent of the nights in 1957 and 2 percent in 1958 (17). Kraus reported a flux level of 4×10^{-22} w/m²/cps for the 27 Mc/s radiation (59). More recently Carr has analyzed the strongest pulses received in 1961 at stations in Florida, Chile, and Australia (5). The strongest bursts at 5 Mc/s represented a received flux of 10^{-18} w/m²/cps, and the energy decreased as the -3.6 power of the frequency. Figure 94 illustrates the rapid decline in intensity with frequency. This figure is a plot of the averages of the five maximum flux densities received at each frequency monitored in Florida, Chile, and Australia during 1961. The 5 Mc/s data have not been included because of the uncertainty of the calibrations. Points at 15 and 20 Mc/s have been added to the original study by Carr and a curve has been drawn through the points instead of the previous straight line. The extrapolation beyond 27.6 Mc/s indicates a cutoff in the neighborhood of 35 Mc/s. The line above 85.5 Mc/s indicates the detection limit of the receiving system in Australia. It is perhaps worthwhile to mention that conditions permitted effective listening at 85.5 Mc/s on 28 nights during the summer of 1961. In 63 hours of monitoring, no pulse exceeding 5×10^{-25} w/m²/cps was detected and during much of this time there was activity at lower frequencies. One should recall that Figure 82 illustrated the decrease in the frequency of occurrence of decameter radiation at the higher frequencies. Just recently a member of the Florida group has arrived at approximate distribution functions for the flux density at each frequency and finds that a plot of the seasonal average intensity (counting all observing

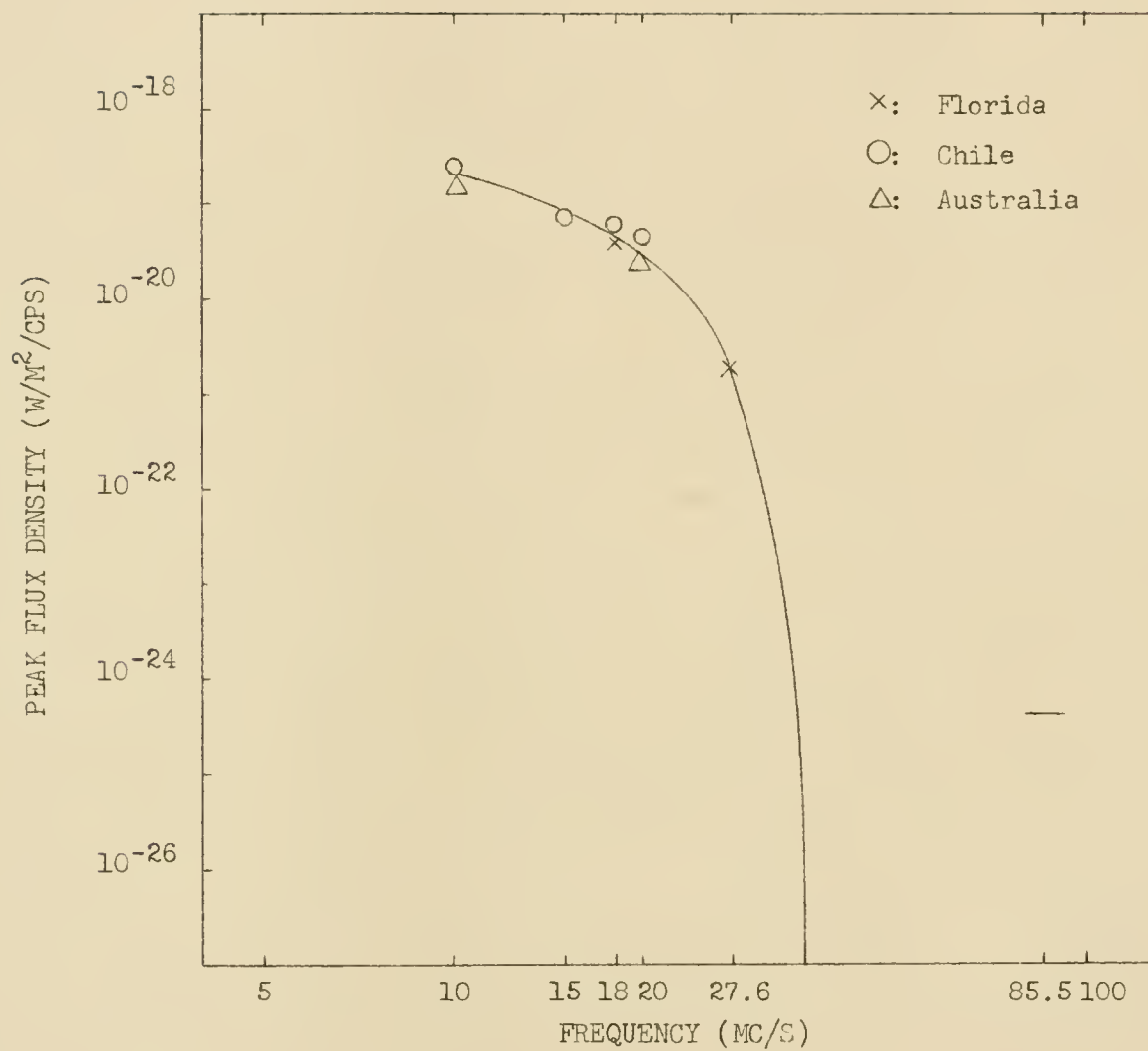


Figure 94.--Spectral distribution of averaged decameter peak flux densities from Jupiter in 1961.

time regardless of whether or not there was Jupiter activity) versus frequency has the same shape as the curve in Figure 94, but the flux values are roughly two orders of magnitude less (84).

Microwave. Early observations of the Jovian microwave radiation around 3 cm. yielded radio temperatures always slightly higher than the values derived from the optical data. The flux densities were calculated to be approximately 1.6×10^{-25} w/m²/cps (85, 86, 87). The microwave component has now been investigated from about 3 to about 70 cm, and the flux appears to remain almost constant near a value of 10^{-25} w/m²/cps. Figure 95 shows the spectral distribution of the Jovian microwave radiation; it was taken from reference 4.

Long-Term Variability

Decameter. The most striking long-term variation in the decameter radiation is the apparent inverse correlation of the planet-wide probability of occurrence with the sunspot cycle that was demonstrated in the first part of Chapter III. The fact that the width of the principal decameter source varies from year to year, also inversely with the sunspot cycle, suggests Jovian ionospheric focusing. There also seems to be a correlation between Jovian activity and the elongation of the planet, which is not yet understood. Some evidence of 8- and 32-day cycles has shown up in the 1957 and 1961 activity plots of Chapter II. Source C appears to vary in activity from year to year in comparison with B.

The dip in Jupiter activity at opposition is interpreted by the writer as evidence that solar plasma plays a significant role in

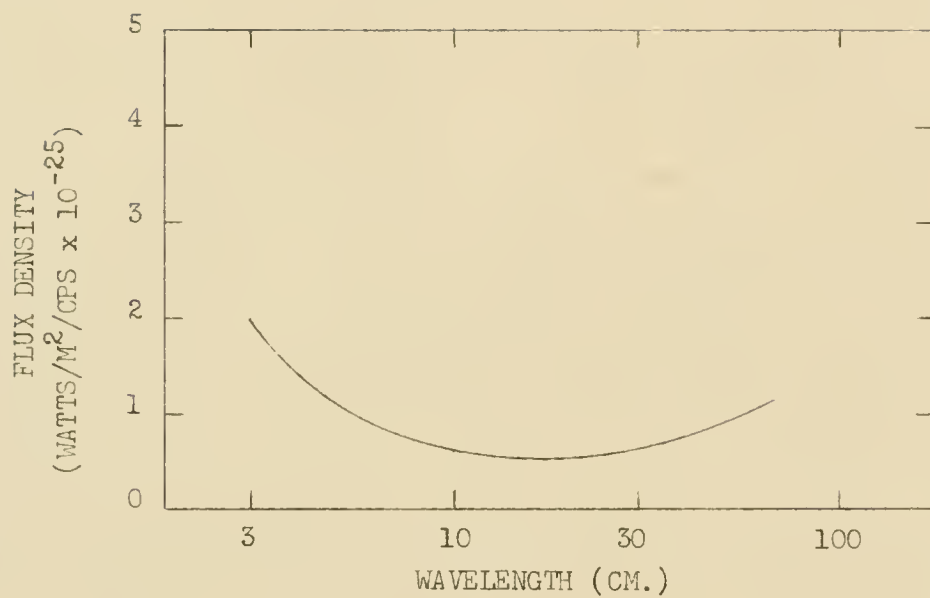


Figure 95.--Spectral distribution of Jovian microwave flux densities (4).

the decameter emission process. The relationship between solar activity and decameter emission is by no means settled. Warwick has inferred from analyzing solar decametric continuum that high velocity particles, which traverse the Earth - Jupiter distance in one or two days, are responsible for the radiation (88). The Florida group reported that decameter storms during the three-month period around opposition in 1960 followed periods of enhanced geomagnetic activity by about 8 days (2). A similar analysis performed in Chapter III on the 1961 data indicates a 3-day delay, but this is not very convincing. All of the three analyses of the variation in the geomagnetic A index around days of strong Jovian emission in 1961 show a null in Ap when Jupiter is most active. This still remains a mystery.

Microwave. There are definite indications of long-term changes in the measured radio emission of Jupiter (89, 90). The value of the equivalent disk temperature at 10.3 cm. dropped from $640^{\circ} \pm 57^{\circ}$ in 1958 to $315^{\circ} \pm 45^{\circ}$ in 1959, and different polarizations of the antenna with respect to the planet account for only a part of the change (89). A similar decrease in flux was observed at 21 and 68 cm. during the summer of 1959 (90).

Many attempts to find a relation between the variability of the microwave radiation and solar activity have been unsuccessful. However, by analyzing 90 observations of Jupiter in 1961 and gauging solar activity by sunspot number, 10.7, and 20 cm. solar flux, M. S. Roberts has reported a positive correlation between Jovian microwave flux density and solar activity for phase lags of 0 to 6 days (91). More recently Huguenin and Roberts (92) have concluded that it is the polarized

component of the decimeter radiation that is correlated with solar activity, while the unpolarized component shows no significant correlation. Their studies indicate that the polarization of the 21 cm. radiation increases with increasing solar activity as measured by 10.7 cm. solar flux. Since solar activity was extremely low during the period of these observations, we must regard the question of solar correlation as unsettled for the present.

Source Dimensions

Decameter. The decameter source region has not yet been resolved; however, the distinct correlation of the radiation with Jovian longitude, as evidenced by the histograms in Chapter II, suggest that the sources are at least as small as the planetary diameter and probably smaller.

Microwave. The microwave source region has been measured by workers at Cal. Tech. and its dimensions are approximately 3 planetary diameters in the equatorial direction and 1 planetary diameter in the polar direction (76, 77). This region, which is outlined in Figure 93, conforms roughly to the shape of the terrestrial Van Allen belts. There appears to be no significant variation in the angular size of the source region with frequency (77).

Theories of Origin

A brief description of the different theories concerning the origin of the non-thermal Jovian radiation and their fit to the empirical data is given below.

Jupiter's Microwave Emission

Thermal emission from a deep atmosphere with a thermal gradient (93) and free-free transitions in a dense Jovian ionosphere (82, 93) have been discounted as probable sources of Jupiter's microwave emission because of contradictions with the experimental data. Since the discovery that the microwave radiation is partially plane polarized (76), attention has been focused on the radiation from electrons trapped in the planet's magnetic field. Field has presented a detailed theory of cyclotron radiation from electrons in a Jovian Van Allen belt (94), but on the basis of the spectrum and time variations in the radiation he has recently concluded that the cyclotron model is inadequate to account for the observations (90).

Synchrotron radiation was first suggested as an explanation of the microwave emission by Drake (62), and has been investigated by Field, Roberts and Stanley, and Davis and Chang (95, 96). Recent measurements by Morris and Berge (77) lend support to the synchrotron model and concur with Field's conclusion that the cyclotron mechanism is inadequate. They find that there is no significant variation in the angular size of the source or polarization with frequency over the range 960 - 1390 Mc/s. This is in agreement with the synchrotron model, since each relativistic electron will emit a continuous spectrum at each point in its trajectory; but it contradicts the cyclotron theory, because non-relativistic electrons radiate at the local gyro frequency at each point in their trajectory, meaning that the position of the emitting region, and the polarization, angular size, and intensity of the source will be frequency-dependent. Theoretical studies by Chang

and Davis (97) indicate that the partially polarized decimeter radiation could be synchrotron emission from shells of relativistic electrons in a dipole field, provided that a large number of the electrons move in relatively flat helices. They estimate a magnetic field strength of 0.1 to 1 gauss in the emitting region and sixty times as much at the poles, electron energies in the range 5 - 75 Mev., and densities of the order of 10^{-2} - 10^{-3} electrons per cm^3 . The field is strong enough to contain the required density of electrons but not so large that the solar wind cannot transfer energy to the fields for acceleration processes. It seems plausible that betatron acceleration leading to flat helices might result from the diffusion of the magnetic field into solar plasma as the plasma penetrates Jupiter's field.

Jupiter's Decameter Emission

The phenomena observed in Jupiter's decametric emission are more numerous and more difficult to account for than those suggested by the microwave measurements. As a result there has been no shortage of proposed theories attempting to explain the observations.

One of the fundamental questions concerning the origin of the decameter waves is whether they emanate from the magnetosphere or are radiated near the Jovian surface. The distinct longitude dependence demonstrated in Chapter II indicates that the sources are linked to the solid disk of the planet, probably through its magnetic field, and are close enough to the surface so that the higher multipole components of the magnetic field affect the source distribution. P. A. Sturrock has suggested five sources of energy capable of generating electromagnetic

waves in the terrestrial magnetosphere: energetic electrons in the radiation belts, the solar wind, bursts of energetic particles from the sun, shock waves in the interplanetary medium, and the rotational energy of the planet (98). Presumably these would also apply to Jupiter. The following mechanisms for converting energy into radio frequency radiation have been proposed to explain the Jovian decameter bursts: spark discharges, chemical explosions, cyclotron or synchrotron radiation, plasma oscillations, hydromagnetic waves, Cerenkov radiation, wave amplification, and Bremsstrahlung. Before discussing these various processes, it would be worthwhile to examine the energy content of the decameter bursts.

The strongest Jovian pulses at 5 Mc/s correspond to a received flux density of 10^{-18} w/m²/cps. It is interesting to note that this is also approximately the upper limit to the intensity of solar bursts in the decameter range and, realizing that Jupiter is at least four times as far from the Earth as is the Sun, the signals from Jupiter are 16 times as strong (99). If it is assumed that the radiation is limited to a 60° cone, the power per unit bandwidth in a strong 5 Mc/s Jovian pulse is 3×10^5 w/cps. The typical bandwidth of a pulse is 1 Mc/s and the average duration is 1 second, giving for the total energy in the pulse a value of 3×10^{11} joules. If the efficiency of conversion into radio energy is of the order of 10^{-5} (see Gallet (24), page 523), then the energy involved is 10^{16} joules, which is considerable.

The ionospheric focusing theory of the Stroms has already been dismissed by the writer as a possible explanation of the decameter bursts on the basis of the considerations in Chapter II.

Spark discharges. C. A. Shain (27) suggested in 1955 that the decameter bursts might be lightning-like discharges in the Jovian atmosphere. A terrestrial lightning discharge radiates about 4×10^{-5} w/cps at 5 Mc/s. If this discharge were transported to Jupiter and the radiation were emitted equally in all directions, it would correspond to a flux density at the Earth of 10^{-29} w/m²/cps. This is 10^{11} times weaker than the strongest decameter bursts at 5 Mc/s (99). Also, terrestrial lightning emits a broad spectrum of radio energy, and the static pulses, which endure for less than a millisecond, are always concentrated in the lower frequencies. In contrast, the Jovian bursts possess narrow bandwidths, typically last for the order of one second, and noise storms frequently drift up or down the spectrum. As early as 1955 F. G. Smith discounted the lightning hypothesis and proposed that the energy for the bursts is supplied by the differential rotation or slippage of the atmospheric belts (60). G. B. Field proposed a dynamo mechanism in 1960, whereby spark discharges result from the voltages induced by Jupiter's magnetic field slipping through the atmosphere (94). More recently investigators at Cal. Tech. have suggested that the decameter radiation is caused by the Jovian Van Allen belt dipping down into Jupiter's atmosphere. Presumably Bremsstrahlung would result.

Chemical explosions. Sagan and Miller have suggested that the sporadic bursts of radio frequency energy might be the result of the explosive polymerization of acetylene in the Jovian atmosphere (100). Considering the magnitude of the energy involved in the radio outbursts, this hypothesis does not appear very attractive.

Plasma oscillations. Gardner and Shain (26), Gallet (24), and Zhelezniakov (101) have favored the idea of plasma oscillations being responsible for the radio noise bursts. There is convincing evidence that such processes occurring on the sun produce solar radio emission, the negative spectral drifts being attributed to radiation sources rising through a plasma of decreasing density. If a plasma (an electrically neutral, highly-ionized gas) is perturbed so as to produce local excesses of electrons or positive ions, then after removal of the impressed force the space-charge density simply oscillates at a frequency characteristic of the medium. When there is no magnetic field, plasma oscillations and transverse electromagnetic waves are independent. The existence of either a steady magnetic field, inhomogeneities, or large amplitudes of the oscillation which produce non-linearities can lead to coupling between the two. Zhelezniakov suggested that plasma oscillations in a Jovian ionosphere of non-uniform electron density give rise to the radio signals from the giant planet. He examined in detail the mechanism involved, but based his calculations on the assumption that the noise pulses are of millisecond duration. Gallet attempted to explain the longitude dependence of the radiation by suggesting that shock waves of volcanic origin excite plasma oscillations (102). This is not unreasonable, considering the amount of internal heat Jupiter must possess. Measurements of the Jovian cloud temperatures yield values too high to be explained by solar heating alone. E. J. Opik estimates that the thermal energy flowing out through one square meter of the Jovian surface is

1.6 times the incident solar energy (103). This is indeed a large figure, considering that the ratio of incident solar energy at the earth's surface to heat from the interior is 30,000 to 1 (99).

It would seem worthwhile to re-examine the plasma oscillation mechanism in the light of the experimental evidence now available.

Cerenkov radiation. J. W. Warwick (29) believes that the decameter bursts are Cerenkov radiation caused by fast electrons precipitating into the Jovian ionosphere from the radiation belts. The sequence of events would be as follows: 1. Localized disturbances occur in the magnetic field at 2 to 3 planetary radii. 2. These cause the precipitation of fast electrons along the lines of force with the excitation of Cerenkov emission. 3. The radiation is directed toward Jupiter and reflects off of the ionosphere or the surface of the planet. 4. An earth-bound observer detects the emission only when the magnetic field and the surface of Jupiter are in the correct orientation relative to the earth, with the additional condition that particles should at that moment precipitate out of the belts. The precipitation of energetic electrons from the geomagnetic field has been observed during magnetic storms (104). One objectionable feature of Warwick's model is that it requires a highly eccentric, decentered magnetic dipole. It is very difficult to postulate a system of core currents which might give rise to such a field. Also, the theory predicts a third source at low frequencies producing storms which drift toward lower frequencies and a fourth source also at low frequencies producing storms which drift upwards in frequency. The 1961 data at 10 Mc/s collected in Chile and Australia do not exhibit

such a fourth source. (See the histograms in Figure 4.) Perhaps during the next few years enough low frequency data will be obtained to permit a conclusive test of this theory.

Wave amplification. G. B. Field has recently presented a detailed analysis of the decameter radiation and proposes a model based on the transfer of energy from fast trapped electrons to weak electromagnetic waves, generating coherent emission of high efficiency (105). He considers the interaction of electrons with waves propagating in the whistler mode, i.e., extraordinary waves propagated parallel to the field lines with phase velocity $< c$. If all gyration phases are present, the electrons whose perpendicular velocity is antiparallel to the electric vector of the wave when the wave frequency is equal to the gyrofrequency are accelerated and take energy from the wave. Electrons of opposite phase are decelerated and give energy to the wave. Considering relativistic effects, he concludes that in the case of waves moving poleward and electrons equator-ward into a weaker field, the decelerated group spends more time in resonance, the net effect being that the wave amplitude grows at the expense of the electrons. Radio emission near the local gyrofrequency results and is directed poleward. Field points out that this process will occur only for energy spectra having an excess of fast electrons. His model assumes a dipole field of only 10 percent eccentricity, which agrees well with the microwave measurements. A weak point of this theory is the longitude dependence of the decameter signals. With the emission originating in the Jovian magnetosphere, far from the planet, it is difficult to imagine how the source distribution arises. Field's suggestion that the longitude

dependence is due to the shadowing effect of the disk of the planet, brought about by the northward displacement of the dipole, does not seem sufficient. Since the radiation would emerge from the back side of Jupiter over the north or south pole, a test of this model would be an interferometric experiment measuring the source extension in the north-south direction, as Field points out.

A process similar to that described by Field is believed by Gallet to be responsible for certain low-frequency radio signals which have been observed on earth (106, 107).

Cyclotron radiation. T. D. Carr first suggested that the elliptical polarization of the Jovian waves could be explained if the radiation were due to solar electrons spiraling in Jupiter's magnetic field (108). He proposed that the correlation with longitude was caused by an inclined dipole not passing through the center of the planet. The implication of a high frequency cutoff in the neighborhood of 35 - 40 Mc/s is that the maximum field strength accessible to the particles is approximately 14 gauss. If fewer particles possessed high pitch angles, this would explain the rapid decline in emission at the higher frequencies. The displacement of the cone of emission toward the polar region could account for the shrinkage in angular extent of the sources as the frequency increases. A. G. Smith has proposed that the decameter emission might be cyclotron radiation from bunches of electrons injected into the Jovian magnetic field and oscillating between conjugate points (58). The B^2 dependence of the energy loss rate suggests that the distribution might be depleted of the steep-helix electrons which encounter the higher polar fields, and this would explain the scarcity

of radiation at the higher frequencies. Evidence that such particle bunches exist in the geomagnetic field is indicated by the periodic precipitation of energetic electrons during magnetic storms (104).

Synchrotron emission is characterized by overlapping multiple harmonics of the cyclotron frequency and a resultant broad spectrum. The fact that the decameter bursts rarely exceed 30 Mc/s and have bandwidths of 10 percent or less is the reason that synchrotron emission has been dismissed as a plausible explanation of the decameter noise storms.

If we receive cyclotron radiation from particles in Jovian Van Allen belts, why don't we detect cyclotron emission from our own radiation belts? At the inner belt $B = .1$ gauss and the gyrofrequency is 300 Kc/s. At the outer belt $B = .01$ gauss and the gyrofrequency is 30 Kc/s. Frequencies this low cannot penetrate the earth's ionosphere (99). The fact that we detect no synchrotron radiation is good evidence that high energy particles are not present in sufficient numbers to generate radiation capable of penetrating the ionosphere.

Coherent cyclotron emission. As a possible mechanism to explain the decameter emission from Jupiter, I have suggested a wave-particle interaction, similar to Field's theory in some respects, which results in the coherent motion of a group of electrons with emission at the local gyrofrequency (109). Suppose for the time being that there are present in Jupiter's magnetosphere electromagnetic waves propagating along lines of B . What is the interaction between these waves and the non-relativistic electrons gyrating in the Jovian radiation belts? At points in the magnetic field where the wave

frequencies are equal to the local electron cyclotron frequencies, conditions are right for the interchange of energy between the waves and the electrons. Assuming a pitch angle of zero and selecting a coordinate system fixed at the center of gyration as shown in Figure 96, where B is directed into the paper along the z -axis, the equation of motion of an electron gyrating in a constant B field and acted upon by a plane polarized electromagnetic wave whose electric vector lies in the yz plane is given by

$$\ddot{y} + \omega_0^2 y = -\frac{e}{m} E_0 \sin \omega_0 t \quad [25]$$

Here $\ddot{y}$ is the second time derivative of y ; ω_0 is the electron cyclotron frequency, which is related to B by equation [11]; e and m are the electronic charge and mass; and $E_0 \sin \omega_0 t$ is the impressed electric field due to the wave.

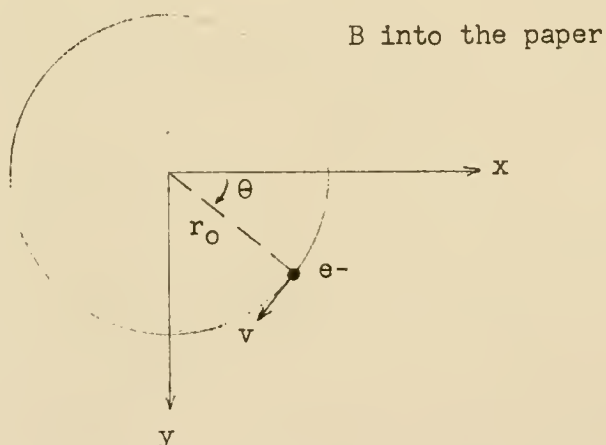


Figure 96.--Coordinate system of gyrating electron.

We need examine only the y equation because the wave is plane polarized in the yz -plane. Equation [25] is the expression for resonance; i.e., the impressed frequency is equal to the natural frequency, with no damping term. The general solution of equation [25] is the following (110):

$$y = A \cos \omega_0 t + C \sin \omega_0 t + \frac{E_0}{2B} t \cos \omega_0 t, \quad [26]$$

where A and C are constants of integration. Applying, as the initial conditions for $t = 0$,

$$\begin{aligned} x_0 &= r_0 \cos \theta_0 \\ y_0 &= r_0 \sin \theta_0 \\ \dot{x}_0 &= -r_0 \omega_0 \sin \theta_0 \\ \dot{y}_0 &= r_0 \omega_0 \cos \theta_0, \end{aligned} \quad [27]$$

the constants are found to be

$$\begin{aligned} A &= r_0 \sin \theta_0 \\ C &= r_0 \cos \theta_0 - \frac{E_0}{2B\omega_0}, \end{aligned} \quad [28]$$

and [27] reduces to

$$\begin{aligned} y &= r_0 \sin \theta_0 \cos \omega_0 t \\ &+ \left(r_0 \cos \theta_0 - \frac{E_0}{2B\omega_0} \right) \sin \omega_0 t + \frac{E_0}{2B} t \cos \omega_0 t. \end{aligned} \quad [29]$$

This expression shows that after a sufficient time the last term dominates and the displacement increases with time. If to begin with there is an equal distribution of electrons in various phases, the end

result will be a phase alignment of those electrons whose gyrofrequency is equal to the wave frequency. This is so because the dominant term in equation [29] does not contain θ_0 . As time goes on, more and more energy will be transferred from the wave to the particles. The expression for the power supplied to the particles by the wave is

$$\begin{aligned}\bar{\mathbf{F}} \cdot \bar{\dot{\mathbf{y}}} = & eE_0 r_0 \omega_0 \sin \theta_0 \sin^2 \omega_0 t \\ & - eE_0 r_0 \omega_0 \cos \theta_0 \cos \omega_0 t \sin \omega_0 t \\ & + \frac{eE_0^2 \omega_0}{2B} t \sin^2 \omega_0 t .\end{aligned}\quad [30]$$

The first term is positive or negative depending on θ_0 , the phase of the electron when the wave arrives. The second term oscillates between positive and negative values. The final term is always positive and grows with time.

It might be that coherent cyclotron radiation from groups of electrons gyrating in phase is the source of the Jovian decameter bursts. If it is true that in the absence of fast electrons the maximum emission would correspond only to the electron temperature, then the mechanism outlined above could not account for the energies observed in the decameter bursts. It would seem advantageous to examine the effects of magnetic field gradients, the cyclotron radiation reaction with the impressed wave, possible damping effects of the thermal electron population, and the amount of energy to be expected from reasonable particle densities.

Now, where do the hypothetical waves which propagate along B come from? One suggestion is the instability resulting from the

interpenetration of solar plasma streams and the Jovian Van Allen plasma. Another possible source is the two-stream instabilities caused by the solar wind impinging on the boundary of Jupiter's magnetosphere. Either of these instabilities might give rise to hydromagnetic waves or plasma oscillations which could couple to produce electromagnetic waves.

Field-aligned ionic ducts. T. D. Carr believes that many of the observed properties of the decameter radiation are not a function of the radiation mechanism, but are consequences of the mode of propagation out of Jupiter's upper atmosphere (48). He assumes that the emitters are located at ionospheric altitudes in or near the auroral zones and proposes that field-aligned columns of enhanced ionization provide the mode of escape. By displacing the magnetic dipole of the planet, he can account for the observed polarization effects. The theory of the guidance of radio and hydromagnetic waves in the earth's magnetosphere has recently been treated in detail by Booker (111).

An attempt has been made to review briefly the mechanisms proposed to account for Jupiter's decametric emission. Most certainly we do not have sufficient data available at present to permit the selection of one particular model to the exclusion of the others. The longitude dependence remains a difficulty to explain. Source extension, spectral characteristics, and more complete polarization information are needed to enable a more critical evaluation of the existing theories. More complete solar wind data and terrestrial radiation belt studies will undoubtedly aid in this task.

CHAPTER V

A SEARCH FOR DECAMETER RADIATION FROM COMET SEKI 1961 f

Comets are the largest objects in the solar system, yet in mass they are airy nothings. The coma (or head) and the tail of a comet are loose swarms of particles held together by gravitational attraction. The extremely low particle densities in comets explain their transparency.

The head of a comet is a tenuous atmosphere of dust and gas molecules. Comet tails fall into two classes, one composed of dust and unionized molecules such as CN and C₂, the other consisting of a plasma of molecular ions like CO⁺ and N₂⁺. The latter, of which about 30 have been observed, show indications of the presence of large accelerating forces by the motions of individual structures.

As a comet approaches the sun, the increased expulsion of matter from its nucleus, together with the increase in molecular emission, causes a rapid increase in total brightness. Equation [31] relates the observed intensity I to the comet's distance from the sun r in astronomical units (112).

$$I = I_0 r^{-n} \quad [31]$$

I_0 is the intensity of light from the comet when r is 1 A.U., while n is a measure of the "sensitivity of reaction" of the comet. Although n ranges from 2 to 6, values near 4 are predominant. As one might

expect, the decrease in the intensity of a comet's light as the 4th power of the distance from the sun means that comets are available for observation only around perihelion.

Nature of Cometary Activity

One of the most striking phenomena in the realm of comet dynamics is the enormous accelerations of tail material away from the sun. At first it was believed that solar radiation pressure alone was responsible, but by calculating the quantum-mechanical cross section for CO^+ ions (a common constituent of plasma tails), Wurm showed that this would not explain the observed accelerations (113). Biermann noticed that the most violent accelerations in the tails of several comets were correlated with geomagnetic activity when the angle comet-sun-earth was not too large, and concluded that the interaction between solar plasma and the ionized gas clouds in comet tails caused the accelerations (114). He suggested that the molecules in a comet's head are ionized through charge-exchange with solar protons, and that the ionized molecules are then accelerated by collisions (momentum transfer) with solar electrons. This mechanism accounts for accelerations of the observed orders of magnitude, i.e., 10^2 to 10^4 cm/sec², assuming solar stream ion densities of 10^3 to 10^5 per cm³.

Alfven has pointed out that such high ion densities are improbable and that the solar stream densities need only be of the order of 10^{-1} or 10^{-2} particles per cm³ if the solar plasma carries with it frozen-in magnetic fields (115). He postulated that when a solar corpuscle stream carrying a transverse B field strikes a comet, shock

waves generate intensive heating with a resulting increase in ionization of the gases in the head. The magnetic lines of force become frozen into the ionized gas and are deformed as the solar stream flows past the comet's head. It is this streaming magnetic field which Alfven relies upon to determine the shape of the comet's tail and to supply electromagnetic forces sufficient to explain the observed accelerations.

A qualitative analysis of the mechanisms of interaction proposed by Biermann and Alfven has been made by Hoyle and Harwit (116, 117). They believe that Biermann's number densities are too high and Alfven's are too low. Using the values of observed geomagnetic field variations at the time of solar storms, they arrive at an upper limit of $\sim 10^2$ per cm^3 , which is consistent with the Chapman-Ferraro estimate of solar particle stream density. The possibility that counter-streaming plasmas might become unstable, resulting in plasma oscillations, is examined and it is concluded that such collective interactions are not likely to explain a large momentum transfer between solar particles and cometary tail ions. On the other hand, they do feel that Biermann's model of charge-exchange governs the plasma dynamics in the comet's head. The calculations of Harwit and Hoyle show that if predominantly transverse magnetic fields are carried in the solar streams, as Alfven suggested, the observed accelerations of tail ions, ejection velocities from comet head, and filamentary structures are expected consequences. They disagree with Alfven in their belief that the magnetic field functions, not as a force field, but rather as a coupling agent to transfer solar proton momentum to comet

ions by providing a short proton-ion interaction distance.

The plasma activity described above is thought to be only a transient phenomenon. Under quiescent conditions, when there are no solar streams with imbedded magnetic fields striking the comet, solar radiation pressure will account for the smaller tail accelerations.

History of Radio Observations of Comets

At least two general processes involving comets are theoretically detectable by radio observations. One is the refraction of radio waves from distant sources as the waves traverse a comet's head or tail. The other is direct electromagnetic emission from comets themselves. The former might provide information concerning ion and electron densities. Optical observations of comets indicate that the electronic densities and energies in the tail are too low to give rise to detectable levels of thermal radiation. It might be possible, however, to detect the direct emission of non-thermal radiation from plasma effects or long-wavelength monochromatic radiation of molecular origin (118).

In the spring of 1957 the Royal Observatory of Belgium and the Ohio State University reported receiving radio signals from comet Arend-Roland. The Belgian group, using an azimuthally mounted 30-foot paraboloid, reported detecting a stable flux above the level of the ordinary fluctuations of the receiver's output when they swept their antenna over the section of sky containing the comet (119). The radiation appeared to come from the lower part of the head, and the maximum

flux density received on 600 Mc/s was calculated to be $\sim 8 \times 10^{-23}$ w/m²/cps, at which time the comet was 0.7 A.U. from the earth. Because of the absence of relevant solar activity, they concluded that the 600 Mc/s radioflux from the comet at the vicinity of perihelion was monochromatic radiation resulting from transitions between fine structure components of the CH molecule. Kraus at Ohio State University was monitoring galactic radiation on 27.6 Mc/s with a lobe-sweeping antenna having a fan-shaped beam 12° in right ascension and 60° in declination, during perihelion passage of the comet (120). From March 11 to May 1, he detected flux levels in a side-lobe of the antenna pattern which did not correspond to the intensity of either the central galactic source or the magnitude of the solar noise index on 80 Mc/s. Kraus concluded that there was some source in the beam producing a blend with the central galactic source, and suggested that this other source might be the comet Arend-Roland. The peak flux density received was 5×10^{-22} w/m²/cps at 27.6 Mc/s. Whitfield at Cambridge, using a 38 Mc/s interferometer, was unable to obtain any evidence of the refraction of radio waves from discrete sources that were eclipsed by the comet (121).

In early 1960 a group of radio astronomers at Jodrell Bank made scans at 240, 610, 1393, and 1420 Mc/s of comet Burnham on four nights, using the 250-foot radio telescope (122). They were unable to detect any radiation. To date, several comets have been observed by radio methods, and the ratio of reports containing negative results to those which reported detectable flux levels is quite large.

Radio Observations of the Close Approach of Comet Seki

Description of Comet Seki

Comet 1961 f was discovered by T. Seki on the day of perihelion passage, October 10, as an eighth magnitude object. As it receded from the sun, the comet passed the descending node on November 5 and moved rapidly southward, becoming invisible from the northern hemisphere. The closest approach to the earth came on November 15, when Seki passed at a distance of about 0.1 A.U. By the end of November the comet was being observed again from the northern hemisphere.

Comet Seki was a diffuse, poorly condensed object, having no sharp nucleus and a very faint fan-shaped tail (123). Figure 97 shows a photograph of the comet taken on October 18 at the Flagstaff Station of the U. S. Naval Observatory with the 40" reflector (124). Notice the narrow, faint tail and gaseous head. Another photograph taken by E. Roemer on November 11 showed the head to be at least 4' in diameter, and a tail extending 22'. The estimates of the total magnitude of the comet ranged from 5 to 8, shortly after discovery.

Orbital Elements

The orbital elements of Comet Seki computed by L. E. Cunningham give a long-period elliptical orbit (125).

$$i = 155^{\circ}.71183$$

$$\Omega = 246^{\circ}.67884$$

$$\omega = 126^{\circ}.61042$$

$$q = 0.6812271 \text{ A.U.}$$



Figure 97.--U.S. Navy photograph of Comet Seki on October 18, 1961, taken by Dr. E. Roemer (40" reflector, 25 minute exposure).

$$e = 0.9919107$$

$$T = 770 \text{ years}$$

Time of perihelion = October 10.64816 U.T., 1961

Figure 98 will be of aid in identifying the elements.

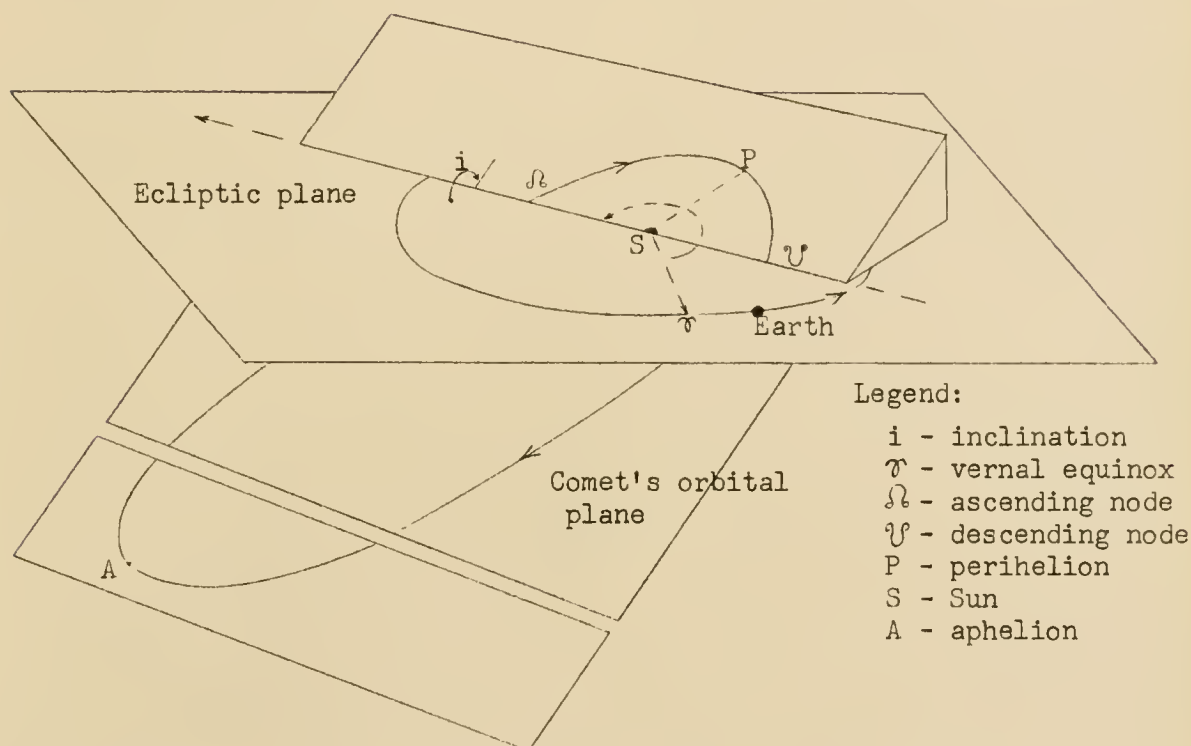


Figure 98.--Elements of the orbit of Comet Seki 1961 f.

Here i is the inclination of the comet's orbital plane. It is the angle between the orbital plane and the ecliptic. A value of $i > 90^\circ$ indicates that the motion of the comet is retrograde. Ω is the longitude of the ascending node of the comet and is measured eastward from the vernal equinox in the plane of the ecliptic; $\Omega = \angle \gamma S \Omega$. The longitude of perihelion measured in the comet's

orbital plane from the ascending node is designated by $\omega = \angle \Omega S P$.

The letter q represents the perihelion distance SP , and e is the eccentricity of the orbit. T is the comet's period. In Figure 98 the position of the earth is shown for November 15, the date of closest approach of Comet Seki.

Ephemeris

Early in November the radio astronomy group at the University of Florida received an ephemeris for Comet 1961 f prepared by Professor Cunningham at Berkeley (126). This information is presented in Table 18.

TABLE 18

Ephemeris for Comet 1961 f by L. Cunningham

Time	Right Ascension (1950.0)		Declination (1950.0)		Earth Distance (A.U.)	Sun Distance (A.U.)	Magnitude	
							4th Power	6th Law
1.0 Nov.	11 ^h	05 ^m .8	+ 9°	57'	.561			
5.0	10	58.6	+ 6	22	.410			
6.0	10	56.1	+ 4	59	.373	.866	4.5	5.8
7.0	10	53.2	+ 3	18	.353			
8.0	10	49.6	+ 1	11	.298			
9.0	10	45.1	- 1	33	.262			
10.0	10	39.3	- 5	09	.226	.916	4.6	5.1
11.0	10	31.2	-10	04	.192			
12.0	10	19.6	-16	59	.160			
13.0	10	00.8	-27	01	.132			
14.0	9	26.5	-41	12	.111			
15.0	8	10.6	-58	03	.102	.982	3.2	3.8
16.0	5	16.8	-68	22	.107			
17.0	2	25.1	-64	13	.125			
18.0	1	10.8	-56	09	.152			
19.0	0	37.2	-49	33	.183	1.037	4.7	5.4
20.0	0	18.8	-44	38	.216			
21.0	0	07.3	-40	58	.252			
25.0	23	46.8	-32	44	.400	1.123	6.8	7.6
29.0	23	39.3	-28	51	.551			
3.0 Dec.	23	36.0	-26	34	.703			

The values of right ascension and declination in Table 18 were transformed into altitude and azimuth settings, as functions of Eastern Standard Time and Atlantic Standard Time, for the antennas in Gainesville and Maipu respectively.

Observing Program

Comet Seki was observed at the Florida station from November 10th to the 14th and from the 18th to the 26th; and at the Chile station from November 11th to the 14th and on the 20th. Figure 99 is a north polar view of the comet's path through the solar system. Values of right ascension are designated around the orbit of Jupiter. The small hash marks on each orbit bracket the positions of the bodies between November 10th and 26th, the period of comet observations.

Instrumentation. At the Florida station the following antenna systems were used in the search for cometary radiation: a 15 Mc/s corner reflector, 18 and 22.2 Mc/s yagis, a 22.2 Mc/s phase-switching interferometer, and an automatic tracking 27.6 Mc/s yagi. The Chile station had the following antennas in operation: a 15 Mc/s broadside array, an 18 Mc/s interferometer, 18 and 20 Mc/s broadside arrays, a 22.2 Mc/s polarimeter, and a 27.6 Mc/s corner reflector. Only the 18 Mc/s yagi and the 22.2 Mc/s interferometer antenna systems in Florida received any signals which might have been of cometary origin.

Figure 100 shows the 18 Mc/s yagi on an alt-azimuth mount. The beam width of this antenna between half-power points is approximately 45° . Its gain is of the order of 12 db compared with a free space dipole, and the minimum detectable flux density using the 18 Mc/s

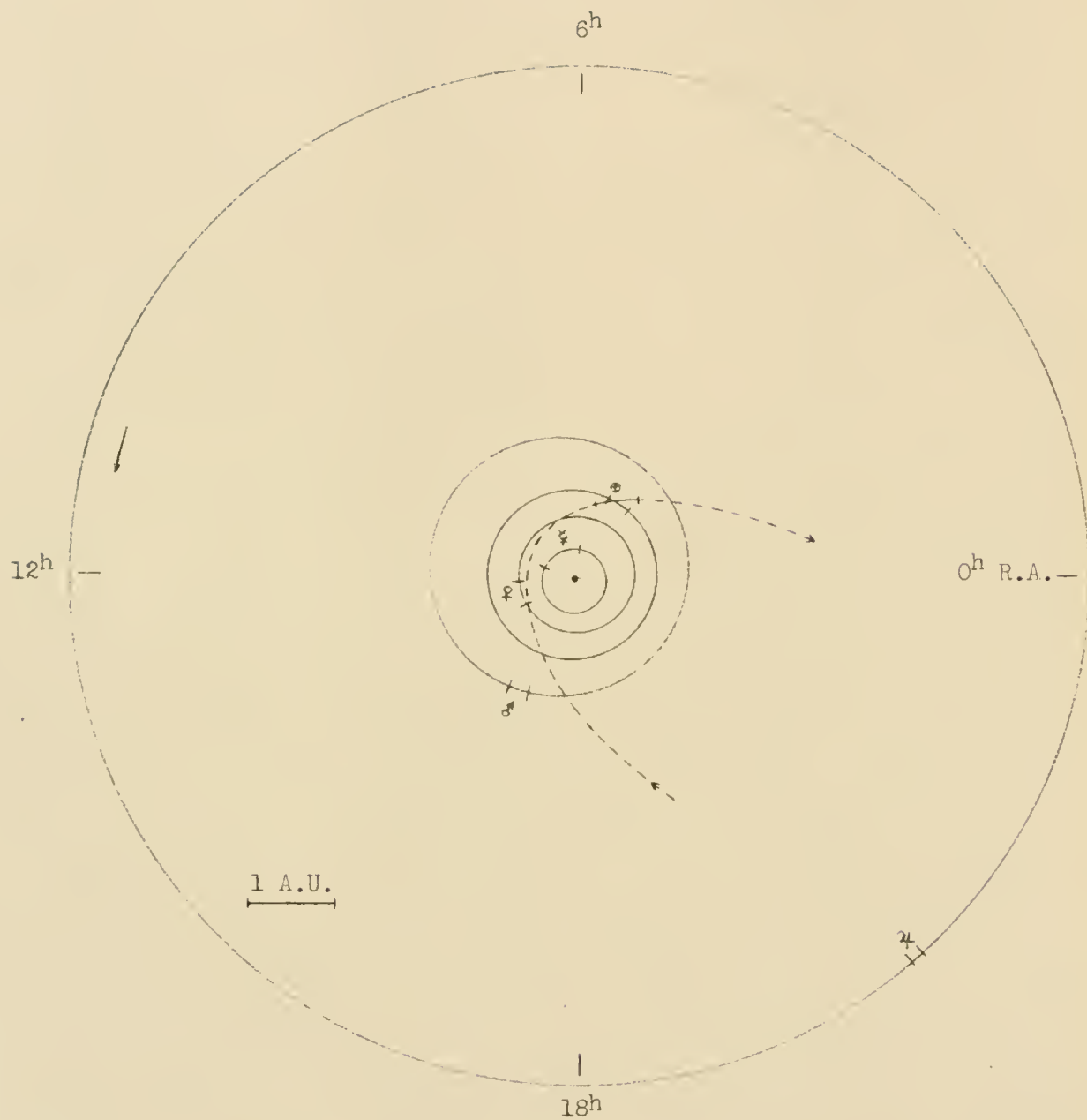


Figure 99.--North polar view of Comet Seki's Path.

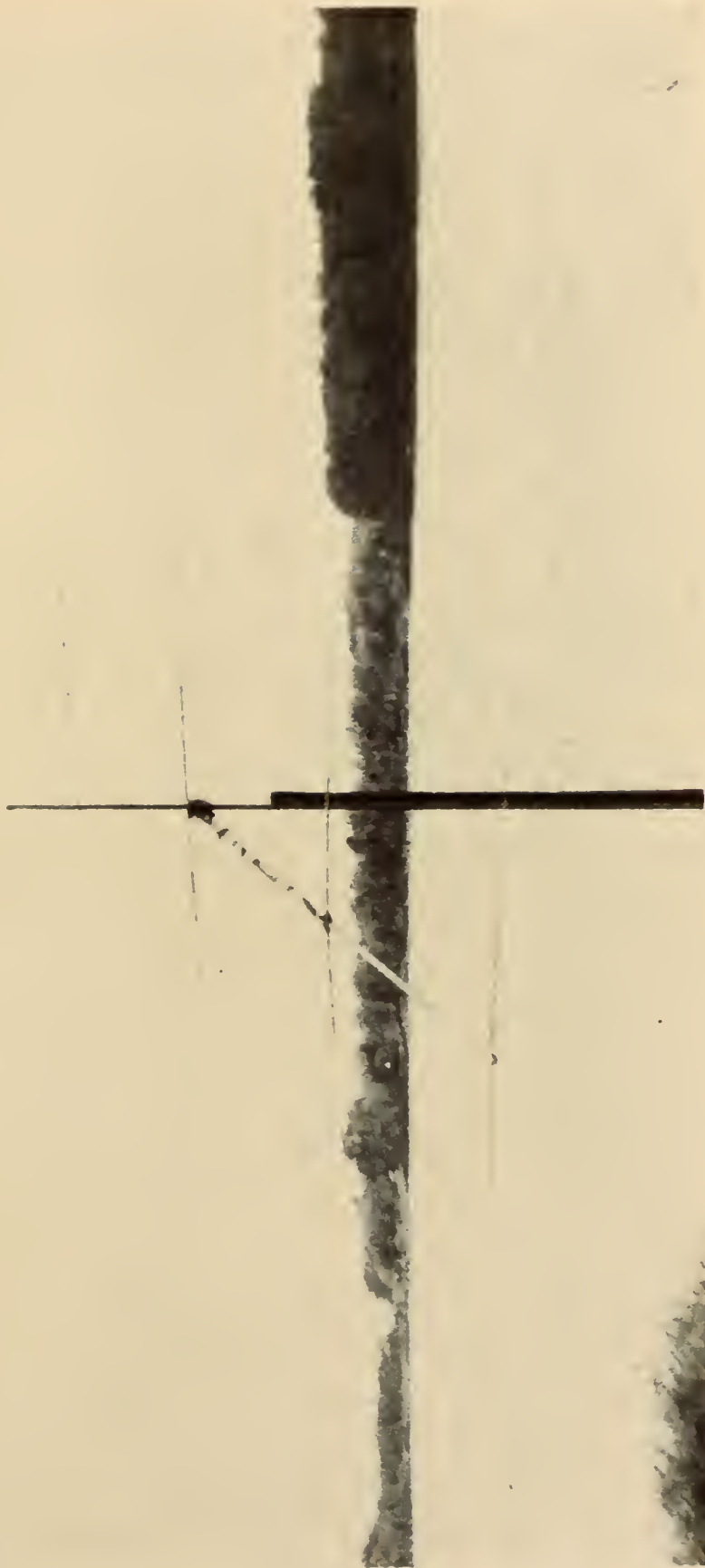


Figure 100.--18 Mc/s yagi antenna at Gainesville, Florida.

receiving system with this yagi is $3 \times 10^{-22} \text{ w/m}^2/\text{cps}$.

Figures 101 and 102 show the east and west broadside arrays which compose the 22.2 Mc/s interferometer at the Florida station. Each array consists of eight 4-collinear-dipole elements situated a quarter wavelength above a reflecting ground plane. The two antennas are spaced 430 feet apart on an east-west line. Figure 103 shows the elevation and plan views of the interferometer pattern (9). The plane of maximum reception is steerable in elevation by adding extra lengths of coaxial cable, and the zenith angle α can be adjusted to 0° , 30° , 45° , or 60° . In the north-south plane the beam width at half-power points is about 30° ; in the east-west plane, about 47° .

Good resolving power is obtained by having a large separation of the antennas, but this leads to difficulties in locating sources because the fringes and their nulls in the interference pattern are hard to identify. The main difficulty is the variation of the background level. The phase-switching interferometer system removes the background radiation by switching alternately a half and a full wave section of cable into one antenna arm and recording the difference in the two outputs (10). Effectively the antenna sees two different sectors of sky. If no discrete source lies in either sector, then approximately equal amounts of background radiation will be detected and the recorded difference will be nearly zero. If there is a discrete source in one sector, then the recorded difference will be due to the discrete source.

The sensitivity of the interferometric system depends upon the gain of the antennas, the sensitivity of the preamplifier, and the



Figure 101.--East section of the 22.2 Mc/s interferometer at Gainesville, Florida.

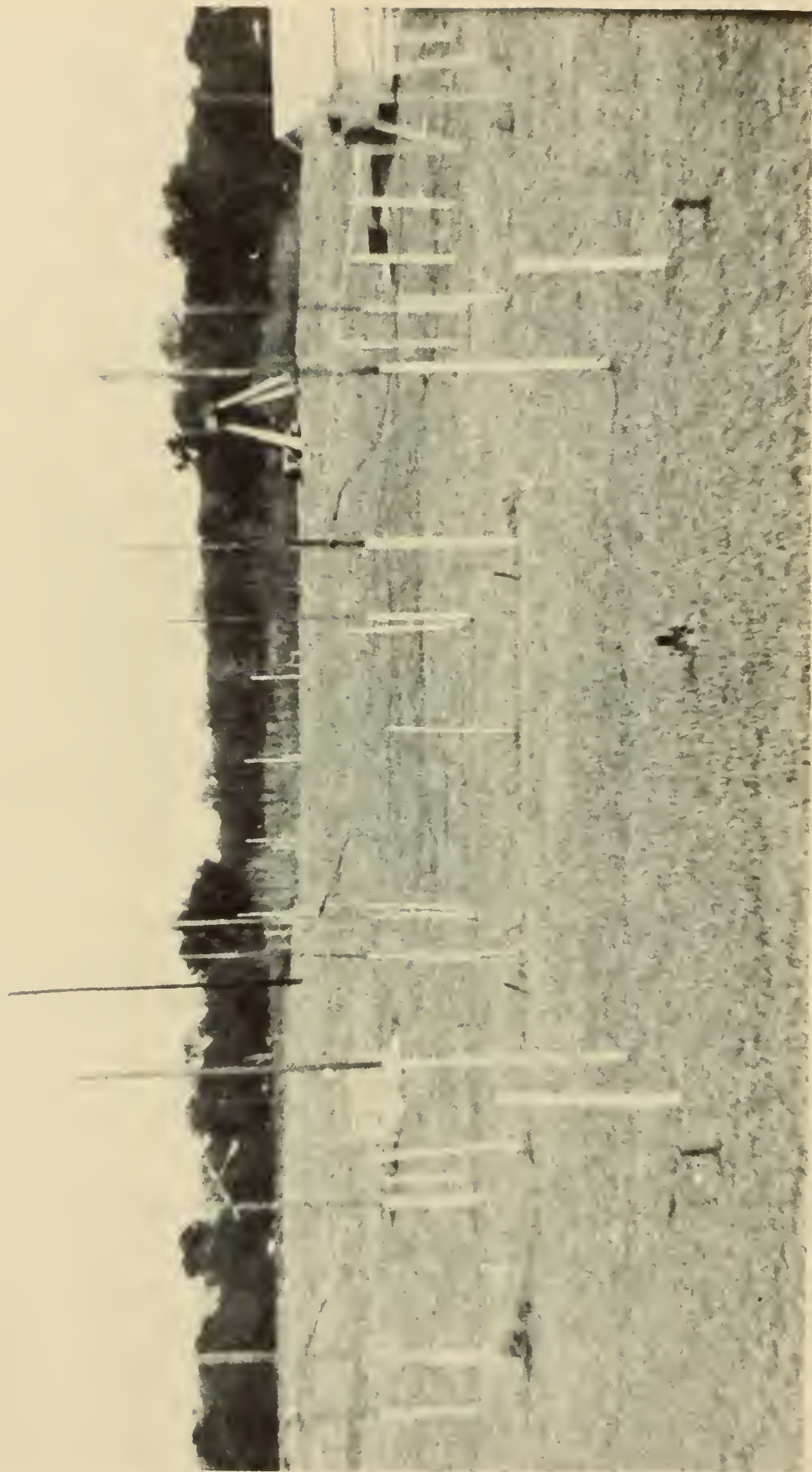


Figure 102.--West section of the 22.2 Mc/s interferometer at Gainesville, Florida.

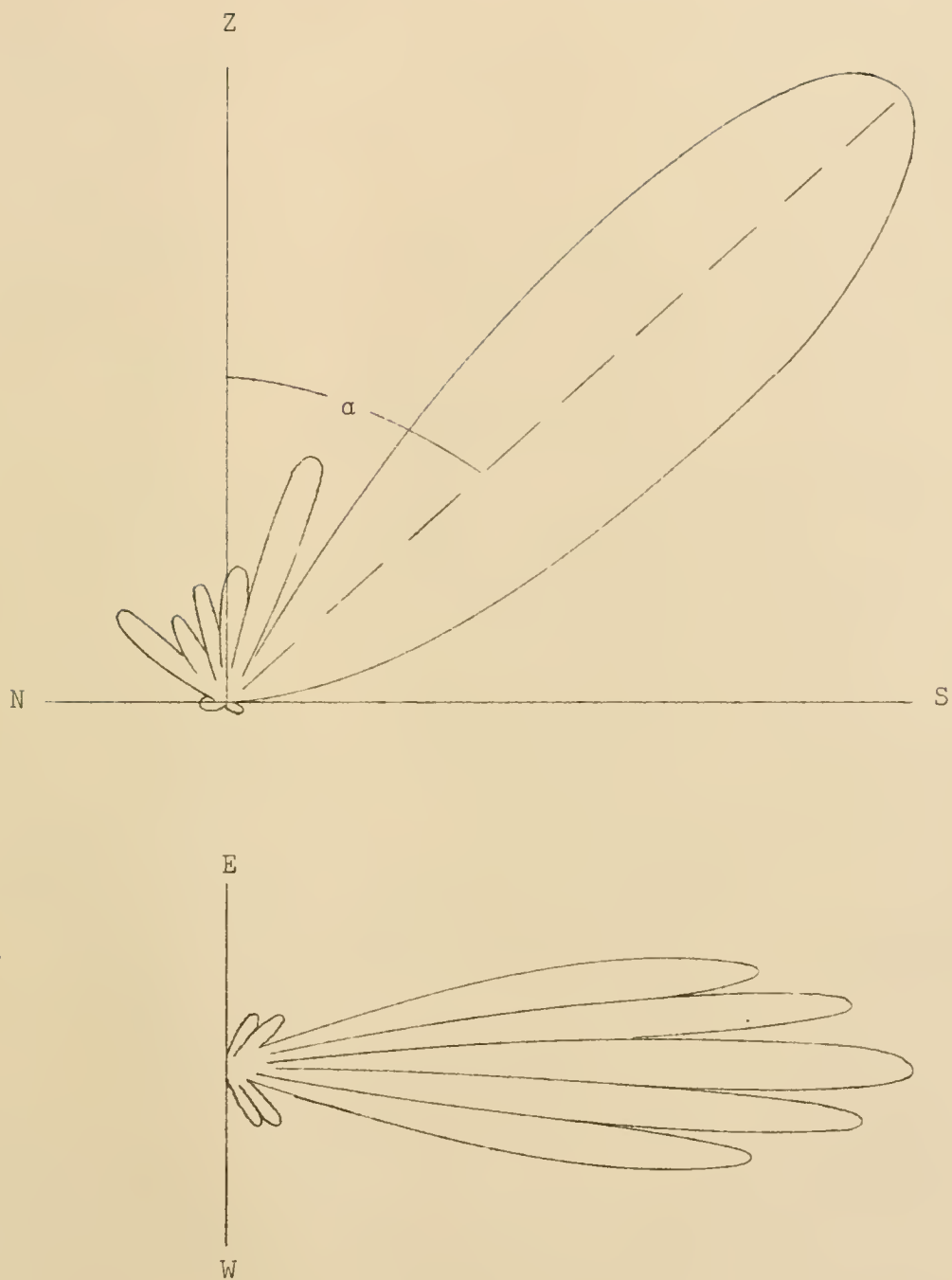


Figure 103.--22.2 Mc/s interferometer pattern.

sensitivity of the receiver. The mean gains of the east and west broadside arrays have been calculated to be 9.2 and 20.8 db respectively (11). Using these values of gain, the maximum receiver sensitivity with a 38-second time constant, and taking into consideration the confusion of sources inherent in an interferometer with broad beam antennas, the minimum detectable source flux should be between 10^{-23} and 10^{-24} w/m²/cps.

Procedure. Most of the antenna systems in Florida and Chile are of the stationary beam type. During the comet observations, Seki appeared to drift through these antenna patterns because of the earth's rotation. Two antenna systems at the Florida station were operated in a different manner. The 27.6 Mc/s yagi was motor driven so that it kept the comet near the center of its beam. The beam of the 18 Mc/s yagi was manually swept over the comet several times each night. Figure 104 shows the position of Comet Seki in the quarter of the celestial sphere extending from the zenith to the southern horizon of the Florida station. The solid lines indicate the motion of the comet from night to night during the period of observation. The lines broken by dots indicate the comet's apparent motion on a given night due to the earth's rotation. Azimuth is marked off along the southern horizon, with 0° being due south. Circles of equal altitude are spaced every 10° up to 60°. The shaded area shows the section of sky covered by the interferometer pattern. From November 13th through the 26th the interferometer was phased 60° south of the zenith. The numbers 10 through 26 mark the comet's positions on those days in November at the designated Eastern Standard Times.

Curve 10-14: 0500 EST
 Curve 18-26: 2100 EST
 Shaded Area: Interferometer
 pattern

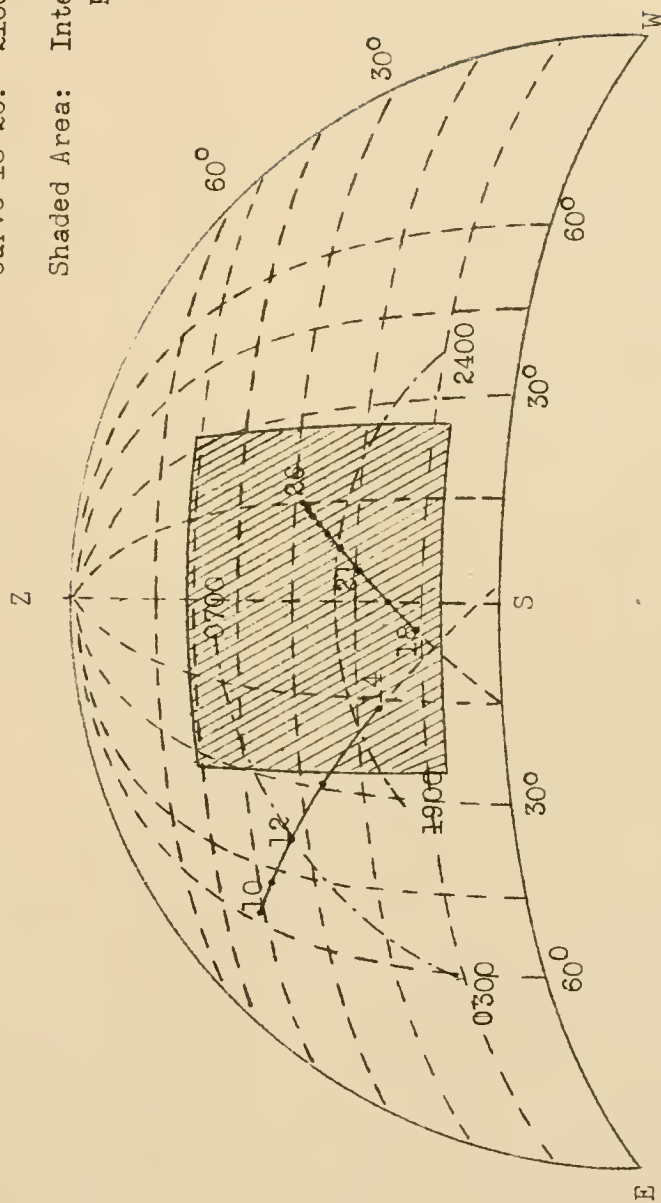


Figure 104. --Alt-azimuth system showing Comet Seki's position in the sky as seen from Gainesville, Florida.

In Chile the comet passed almost directly overhead. Figure 105 shows the zenith view from the Chile station and the numbers 11 to 20 refer to the days of November. The solid line indicates the comet's motion from night to night, and the broken lines, the apparent motion on a given night due to the rotation of the earth.

Scans of Comet Seki were made on 13 nights at 18 Mc/s. A typical azimuth scan consisted of sweeping the antenna from 45° east of the comet, over the comet's position, to 45° west of the comet in one minute. A scan rate of 1.5° per second was maintained throughout the observing period, and the elevation of the yagi was 45° . During scans the pen recorder was operated at a speed of 1.5" per minute. A stop watch was used, and the charts were marked to identify the antenna position with time. If Comet Seki continuously emitted 18 Mc/s radiation, then each sweep of the antenna over the comet's position should trace out the antenna pattern on the pen recording.

The period of time to observe one complete fringe in the output of the 22.2 Mc/s phase-switching interferometer system is given by the following expression:

$$T = \frac{229.2\lambda}{d \cos \delta} . \quad [32]$$

Here, λ is the wavelength (13.5 meters for 22.2 Mc/s), d is the distance between the antennas (131 meters at the Florida station), δ is the declination of the source, and T is in sidereal minutes. The value of T for the radio source Cygnus A is approximately 32 minutes. Since the east-west motion of the comet through the

Curve 11-14: 0530 Chile time

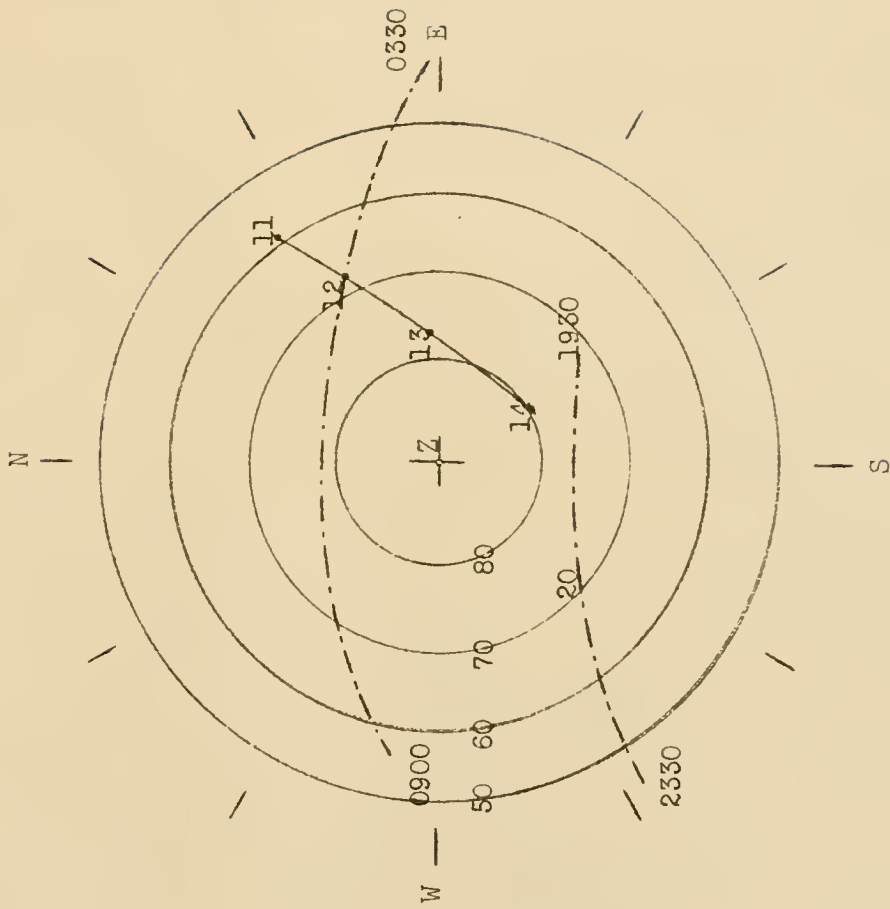


Figure 105.--Zenith view from Chile showing Comet Seki's position in the sky.

interferometer pattern was essentially that caused by the earth's rotation (the comet's motion on the celestial sphere was less than 2° per hour), calculations based on the declination of Seki yield fringe periods ranging from 25 to 38 minutes. If Seki was emitting continuously on 22.2 Mc/s, the fringes produced would be difficult to distinguish from those of the radio sources Cassiopeia and Cygnus A when they also were in the antenna pattern, unless the comet's fringes appeared as harmonics superimposed on the radio star fringes. For comparison purposes a calibration run was made on November 16th when the comet was below the southern horizon at the Florida station.

Evaluation of the Data

The results of an analysis of the data obtained during the comet observations from Florida are presented in Table 19. The Chile data taken November 11 through 14 and November 20 showed no signs of comet emissions. All times in Table 18 are Eastern Standard Time. The dashes "-" mean that there was no effective comet watch on that date with a particular antenna system. "Nothing" means no signal was recognized that might have been of cometary origin. The values of K_p , the geomagnetic planetary 3-hour range index, for November 10 through 16 are those for 0530 Eastern Standard Time; for November 17 through 26, they are for 0130 Eastern Standard Time. The only signals that might have been from Comet Seki were those received while scanning the position of the comet with the 18 Mc/s yagi on November 12, 13, and 14, and the 22.2 Mc/s interferometer fringes on November 14, 18, 19, 20, and 21.

TABLE 19

Results of the Analysis of Comet Seki
Observations Made from Florida

Date	22.2 Mc/s interferometer	18 Mc/s yagi	15 Mc/s corner reflector	22.2 Mc/s yagi	27 Mc/s yagi	K _p
Nov. 10	-	-	-	-	Nothing	1
11	Nothing	Nothing**	-	-	Nothing	0+
12	Weak fringes*	3 possible 0523, 0526, 0612	-	-	Nothing	2+
13	Nothing	2 possible 0532, 0544	Nothing	-	Nothing	1-
14	Weak fringes 0515 - 0638	First series of scans (0335) and second (0400) show bump 10° east of comet; first scan of fourth series (0500) shows rise in level 20° west of comet	Nothing	-	Nothing	2
15	-	-	-	-	-	0+
16†	No fringes	Most of rises in level during scans on 14th must have been due to background; however, some bumps are missing	Calibration	-	Calibration	0+

TABLE 19 --Continued

Date	22.2 Mc/s interferometer	18 Mc/s yagi	15 Mc/s corner reflector	22.2 Mc/s yagi	27 Mc/s yagi	K _p
Nov. 17	Calibration	-	-	-	-	2+
18	Signal superimposed on fringe of Cassiopeia A	Nothing	Nothing	Nothing	Nothing	5
19	Deflections superimposed on Cass A fringes; appear to have some period as Cass A	Nothing	Nothing	Nothing	Nothing	4+
20	Same as 19th	Nothing	Nothing	Nothing	Nothing	0+
21	Few deflections on Cass A fringes	Nothing	Nothing	Nothing	Nothing	3
22	Only Cass A fringes	Nothing	Nothing	Nothing	Nothing	2
23	Only Cass A fringes	Nothing	Nothing	Nothing	Nothing	0
24	Only Cass A fringes	Nothing	Nothing	Nothing	-	1-
25	Only Cass A fringes	Nothing	Nothing	Nothing	-	1-
26	Only Cass A fringes	Nothing	Nothing	Nothing	-	0

* It was later discovered that on this date the two sections of the interferometer were phased for different zenith angles. The east array was phased 30° south, while the west array was phased 45° south.

** The pen recorder speed was too slow to resolve the antenna scans.

† Calibration run. The comet was below the southern horizon.

An examination of the 18 Mc/s pen recordings of November 12 and 13 revealed that out of 37 scans, only 5 showed suspicious increases in noise level as the beam swept over the position of the comet. The times of these suspicious events are given in Table 19. On November 14 many of the antenna scans produced "bumps" on the record. It was decided that a calibration run should be made on November 16, when the comet had disappeared over the southern horizon. On this date all of the antenna systems were operated as they had been on November 10 through 14. Sweeps were made with the 18 Mc/s yagi at the sidereal times corresponding to the scans on the 14th. A comparison of the calibration record with the record of scans made on the 14th showed that most of the bumps on the November 14 scans were also present on the corresponding scans of the calibration record. This indicates that most of the noise level increases were due to the background radiation. (It was determined that the source was not the galactic center.) But, some of the bumps on the November 14 record were missing on the calibration scans. Figure 106 shows the record of such a scan made on November 14 at approximately 0500 EST. Time increases from right to left; hence, the antenna was swept from east to west over the comet's position. The center of the maximum lies about 20° west of the comet.

The 22.2 Mc/s interferometer records of November 14, 18, and 19 were found to warrant careful scrutiny. The weak fringes detected on the 12th were considered unreliable because of the antenna phasing error. Figure 107 shows a comparison of the 22.2 Mc/s record made November 14th with the corresponding section of the 22.2 Mc/s calibration record made on November 16th. The upper record suggests fringes

18 Y RECORD

NOV. 14, 1961

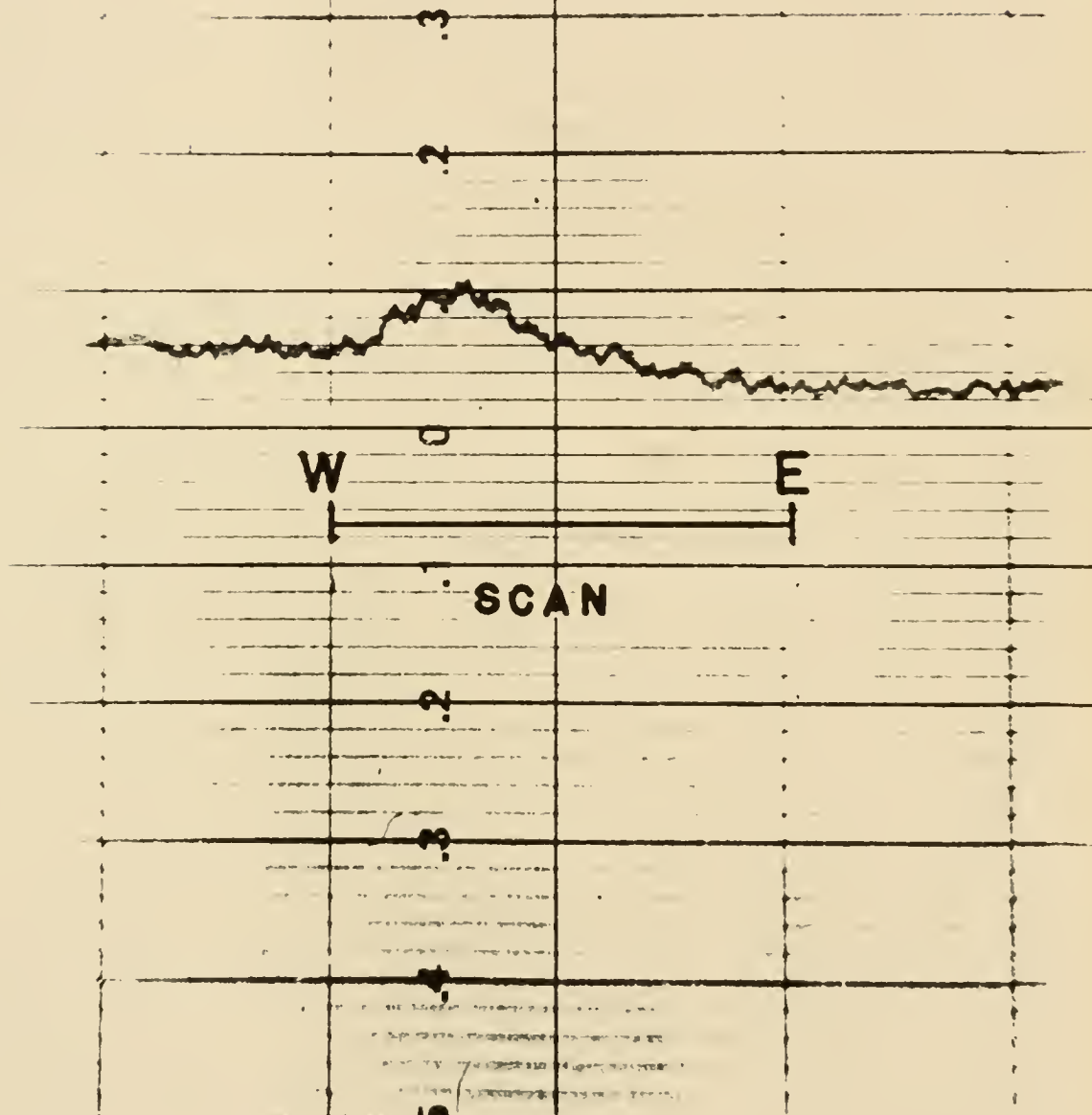


Figure 106.--18 Mc/s scan record of Comet Seki taken in Florida.

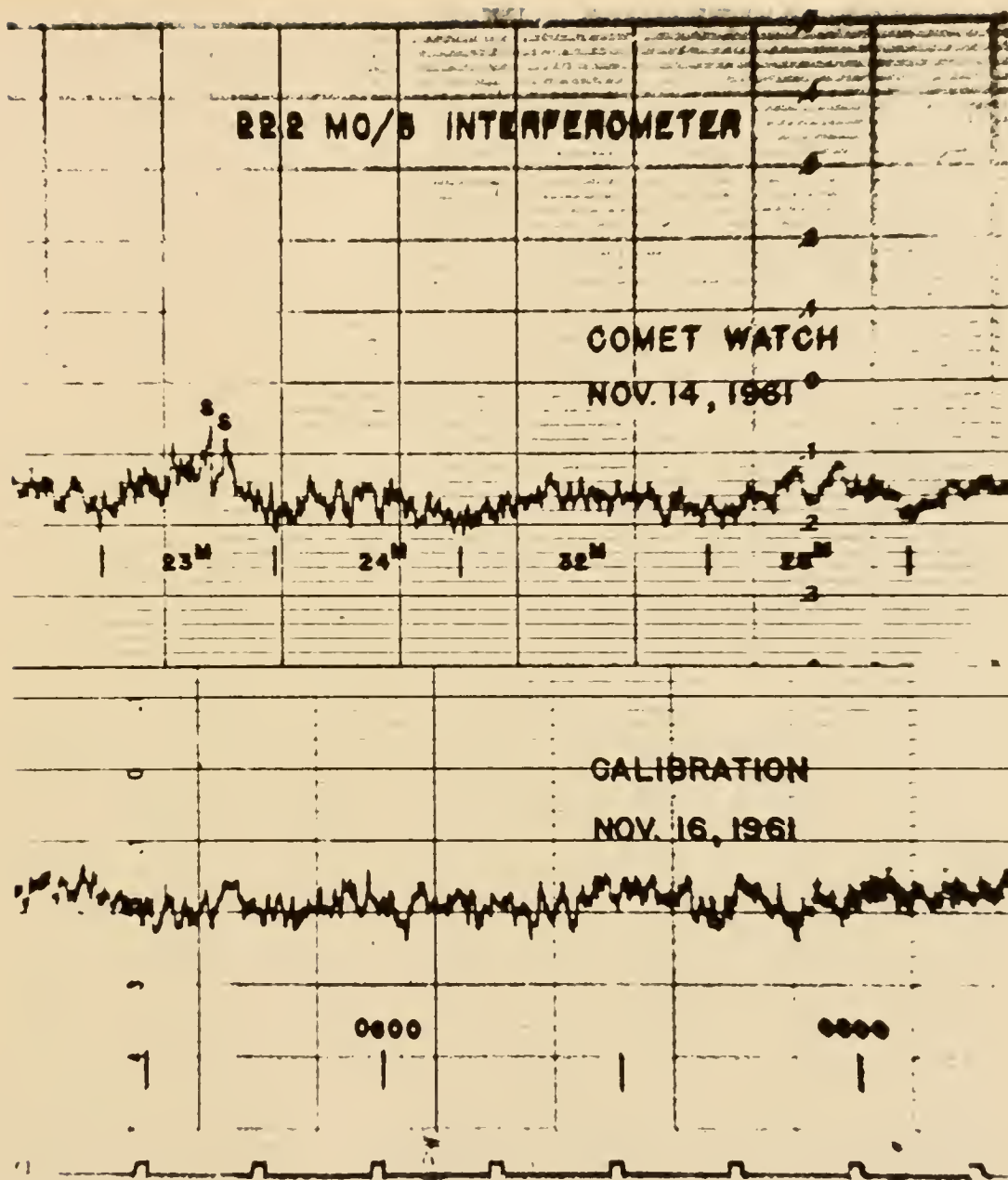


Figure 107.--22.2 Mc/s interferometer records taken in Florida on November 14 and 16, 1961.

with spacings of 23, 24, 32, and 28 minutes. The main fringe at 0620 EST occurred when the comet was due south; i.e., centered in the interferometer pattern. Radio station interference is signified by s. The record made on November 16, when the comet had passed below the Gainesville horizon, shows no such fringes. The theoretical fringe spacing for radiation coming from the declination of Comet Seki (-41°) on November 14, 1961, is found to be 32.5 minutes using equation [32].

Figure 108 shows a comparison of the interferometer records taken during the comet watches of November 18 and 19 with the calibration run of November 17. The records of the 18th and 19th show signals superimposed on the fringes produced by Cassiopeia A. (The flux density of Cassiopeia A at 22.2 Mc/s is $\sim 4.6 \times 10^{-22}$ w/m²/cps (127).) The calibration run of the 17th, when the comet had dropped below the horizon, shows no such deflections--only the smooth fringes due to Cassiopeia A. Again "s" indicates radio station interference. The time scale is marked across the bottom of the record in EST. Notice that the fringe period of Cassiopeia A on the calibration record ($\sim 45^m$) is very nearly the same as the signal period on the 19th (43^m). It is not likely that the deflections were produced by Jupiter. On November 18 Jupiter transit was at 1700 EST, and by 1830 the giant planet was almost out of the antenna beam. If Jupiter were emitting continuously for the three-hour period, then its declination (-20°) would imply a fringe spacing of 26^m . Seki's declination on the 19th (-49°) would yield a fringe period of $37^m.4$. It is possible that equipment trouble or interference was producing these strong deflections. Another possibility is scintillations of the radiation from Cassiopeia A produced by

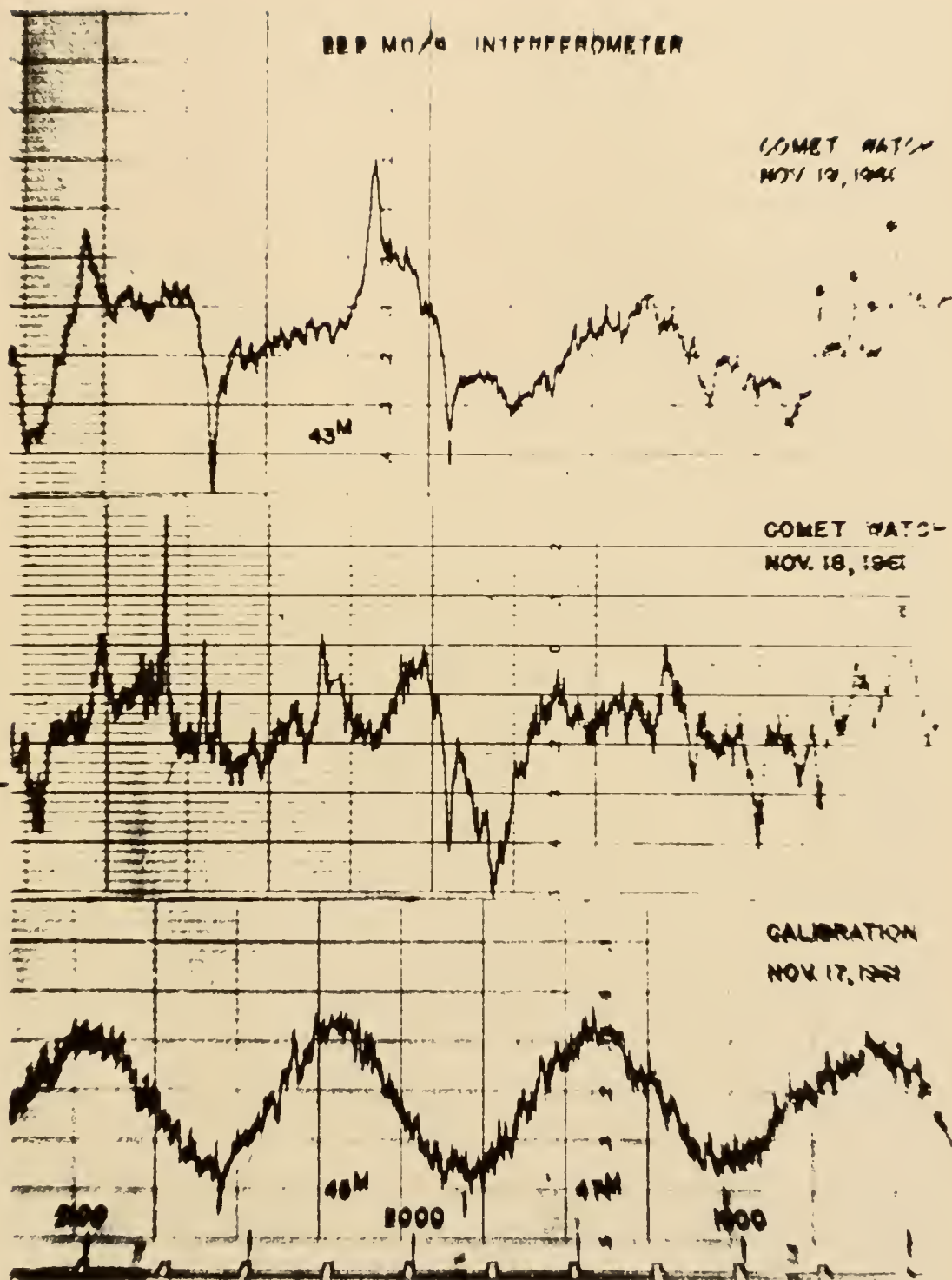


Figure 108.--22.2 Mc/s interferometer records taken in Florida on November 17, 18, and 19, 1961.

irregularities of electron density in the ionosphere. The periods of the fluctuations on the 18th and 19th correspond to a source declination about equal to that of Cassiopeia A. This is also true of the deflections on the record taken November 20 (not shown). It is interesting, however, that these deflections appeared just when the comet again became visible over the southern horizon.

The column of K_p values, which by implication measure solar particle-flux by its magnetic effects, was included in Table 19 because, as mentioned earlier, there is evidence that solar stimulation could be a source of comet radiation. On the K_p scale, 0 means very quiet and 9 extremely disturbed. It has also been discovered that the rate of scintillation of radio stars increases under magnetically disturbed conditions (69). On the calibration nights (November 16 and 17) K_p was quite low. When deflections were observed superimposed on the fringes produced by Cassiopeia A, the K_p values were relatively higher. Since the periods observed did not correspond to the declination of the comet, it is reasonable to assume that these deflections were scintillations of Cassiopeia A.

If comet Seki emitted sporadic 22.2 Mc/s radiation in pulses of greater than one second duration, then one might expect Jupiter-type bursts on the interferometer system. No such pulses were found on the comet records. A disadvantage in detecting short pulses of radiation is that the noise level of the phase-switching interferometer is quite high with time constants of the size necessary to make these observations.

Conclusions

From the interferometer records obtained during November, 1961, one can conclude that during its close approach to Earth, Comet Seki did not continuously emit 22.2 Mc/s radiation of flux density $> 10^{-23}$ w/m²/cps. It is possible that the comet radiated quasi-continuously in the decameter range. The deflections superimposed on the Cassiopeia A fringes of November 18 and 19 are believed to have been scintillations caused by irregular refraction in the ionosphere. The causes of some of the bumps on the 18 Mc/s scan records have not been ascertained. Perhaps the biggest mystery is the comparison shown in Figure 107. The fringe period on the record of November 14 is very close to the theoretical fringe spacing for radiation from a source at the declination of Comet Seki on that date. The calibration run on November 16 made at the corresponding sidereal time shows no fringes. This one piece of data collected by the Florida group on November 14 is the strongest evidence that Comet Seki might be a quasi-continuous source of decameter emission.

How do the results of the Comet Seki observations influence the general question of cometary emission? It is the opinion of the writer that the search for direct long-wavelength radiation from comets has been, up to the present, inconclusive.

CHAPTER VI

SUMMARY

For several years the planet Jupiter has been known to be a strong source of non-thermal radiation in the decimeter and decameter wavelength ranges. An analysis of data collected during the 1961 observing season at radio observatories in Florida and Chile has confirmed and strengthened previous conclusions regarding the Jovian decameter emission, while providing a better understanding of the source distribution at various frequencies and the role played by solar particles.

Methods of merging the data from different stations and different years using an IBM 709 computer have produced probability histograms for frequencies in the range from 10 Mc/s to 31 Mc/s. These histograms show the three principal decameter sources localized in Jovian longitude System III, which rotates with a period of $9^{\text{h}} 55^{\text{m}} 29^{\text{s}}.37$. The locations and widths of the histogram peaks for different frequencies are to be found in Table 4. Source B appears broadened, and it is split on the 18, 20, and 22.2 Mc/s histograms, suggesting the possible existence of two closely-spaced sources. Because of this evidence, the postulation of a quadrupole configuration for the Jovian magnetic field seems justified. Source C almost disappears at frequencies above 18 Mc/s.

Long-term changes in the activity of source C relative to A and B have been found.

The longitude shift of the histogram peaks with frequency (see Figure 27) is now considered a real effect and a possible explanation involving radial motion of the source of emission has been offered. The directional character of the sources and the decrease in the width of the histogram peaks with increasing frequency (see Figure 29) is also explainable in terms of a Jovian ionosphere and a radial motion or a latitude displacement of the emission zones (see Figure 30).

In a preliminary analysis, no well-defined variation in the intensity of the Jovian emission with longitude has appeared.

Activity studies show some indications of the 8-day and 32-day cycles in Jovian activity that were recognized in the 1957 Florida data but subsequently disappeared. Smoothing techniques remove some of the day-to-day bunching of the Jupiter radiation and make these cycles discernible. A comparison of Jupiter noise storm duration with the angular rate of the planet as seen from the Earth contradicts the Stroms' theory of Jovian ionospheric focusing of the energy from radio stars as an explanation of the decameter emission (see Figure 49).

The general increase in observed Jupiter activity with the elongation of the planet is quite evident from the analysis of the 12 months of data obtained during the 1961 apparition (see Figures 50 and 51). It is concluded that neither observing conditions nor the Earth-Jupiter distance is the cause of this effect. A natural suggestion is the attenuation of the Jovian signals by the solar corona

or inhomogeneities, such as plasma clouds, in the interplanetary medium. It is the conclusion of the writer that the decrease in Jupiter activity around opposition (see Figures 50, 51, and 52) may be caused by the deflection of solar plasma by the Earth's magnetosphere, i.e., that solar plasma plays a fundamental role in the decameter emission process. The search for a similar decrease in Jupiter activity at zenocentric inferior conjunctions of Mercury, Venus, and Mars was inconclusive. A weak point in the deduction that particle stream deviation by the earth's magnetosphere causes a decrease in Jovian activity at opposition is the relatively short time duration of the eclipse of the solar disk by the terrestrial magnetosphere.

The search for correlations between solar variables and Jupiter's decameter emission has been continued with the 1961 data. The 8-day delay between geomagnetic storms and Jovian emission around opposition reported by the Florida group in 1960 was not found in the 1961 data. A Chree analysis of geomagnetic index A_p , sunspot number, and flare activity in the central, west, and east sections of the sun as seen from Jupiter did not reveal any prominent short-term correlations with Jovian activity. There is an indication of a 3-day delay between geomagnetic activity and Jovian emission in 1961, but it is not very convincing. Both 1960 and 1961 Chree analyses of A_p revealed a null on the day of strong Jovian emission, indicating a quiescent condition of the terrestrial magnetic field. This effect warrants further examination.

Five polar cap absorption events occurred during the 1961 apparition and on all of these dates there was Jupiter activity.

More data are needed before any firm conclusions can be drawn.

The 1961 data confirm the long-term inverse correlation of Jovian decameter activity with the sunspot cycle. This, along with the inverse correlation of histogram peak width with sunspot number (see Figure 60), would be expected of radiation undergoing ionospheric-type focusing. The Sun's influence on the decameter emission process remains a big question, and more analysis is most certainly desirable.

A synopsis of the experimental data pertaining to the decimeter and decameter emission, including the 1961 results, has been presented, followed by a discussion of the theories of origin of the non-thermal radiation from Jupiter. The microwave data strongly imply the existence of a Jovian radiation belt, lending favor to the models proposing the generation of decameter emission in the planet's magnetosphere. The longitude distribution of the sources is difficult to explain by such a model. Plasma oscillations and wave-particle interactions producing emission near the gyrofrequency seem plausible mechanisms of generation. The decline in the intensity of the decameter emission with frequency (see Figure 94) implies a cutoff near 35 Mc/s. This, along with polarization data analyses, give a value of about 14 gauss for the maximum magnetic field strength in the emission zone.

Before one model can be chosen to the exclusion of the others, more information is needed regarding source extension, and the spectrum, and polarization of the radiation. The degree to which the Jovian signals are modified by the terrestrial ionosphere is still a mystery.

During two weeks in November, 1961, the University of Florida Radio Observatory monitored the close approach of Comet Seki 1961 f in an effort to detect decameter emission. Some of the records obtained showed deflections that might have been of cometary origin. Other deflections were attributed to scintillations of the radio star Cassiopeia A. It was concluded from interferometric data that Comet Seki did not emit 22.2 Mc/s radiation of flux density greater than 10^{-23} w/m²/cps during the period of observation. Up to the present, the search for direct long-wavelength radiation from comets has been inconclusive.

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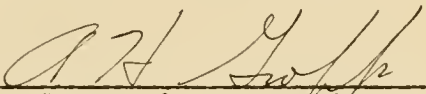
BIOGRAPHICAL SKETCH

Norman Frank Six, Jr. was born July 24, 1935, in Tampa, Florida. He graduated from H. B. Plant High School (Tampa) in 1953 and attended the United States Naval Academy from June of that year to December 1954. In February 1955 he entered the University of Florida and, majoring in physics, completed the requirements for the Bachelor of Science Degree in June, 1957. Upon graduation he received a Hughes Master of Science Fellowship and began part-time employment with Hughes Aircraft Company as a member of the technical staff. He received the Master of Science Degree in Applied Physics from the University of California at Los Angeles in June, 1959. In September, 1959, he again entered the University of Florida, following a course of study and research leading to the degree Doctor of Philosophy in April, 1963. During this period he held both teaching and research assistantships.

He is a charter member and former officer of the University of Florida chapter of Sigma Pi Sigma.

This dissertation was prepared under the direction of the chairman of the candidate's supervisory committee and has been approved by all members of that committee. It was submitted to the Dean of the College of Arts and Sciences and to the Graduate Council, and was approved as partial fulfillment of the requirements for the degree of Doctor of Philosophy.

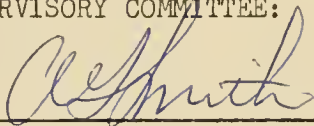
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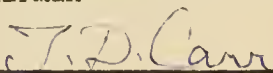
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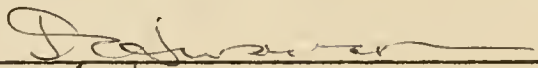
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